Chapter Five

Solar Energy: The Beckoning Opportunity

This chapter will investigate the potential of solar energy as a natural source of energy for buildings. From the beginning of the energy crisis in the early 1970s solar energy has been heralded as a readily available source of heat for virtually any application. Closer examination shows that while solar energy may be a very useful and convenient source of energy for some applications, it is not at all appropriate for other applications.

The effective utilization of solar energy, can make at least the 'sunshine states' of the USA virtually independent of fossil fuel for homes.

Solar energy is ...

- **Abundantly available in most regions of the world.**
- **A natural source of energy that is available most of the time.**
- **A direct source of heat that can be readily captured through absorption.**
- **A free and completely unpolluted source of heat.**
- **Controllable through shading devices and/or reflection (i.e., special glass).**
- **Not impacted by air movement since it is transmitted by radiation.**

Figure 5.1: Solar energy promises

Solar energy is unlikely to provide more than 20% of the entire US energy consumption by 2020.

Solar energy is ...

- **A low intensity (i.e., low temperature) heat source that is not adequate for most industrial heat requirements.**
- **Available for only a portion of the 24-hour day (i.e., 8 to 12 hours/day).**
- **Relatively expensive to collect, control and store.**
- **Sometimes not available for days due to inclement weather.**
- **Often (mostly) not an acceptable solution without a back-up system.**

Figure 5.2: Solar energy reality

5.1 Opportunities and Limitations

Although solar energy is the world's most abundant source of energy, and although it is free, and although it is completely unpolluted (Figure 5.1), it is unlikely that solar energy will account for more than 20% of the entire energy consumption in the US by the year 2020 (Figure 5.2). The fact is that the collection and utilization of solar energy carries with it a number of problems:

1. Solar energy constitutes a low-quality source of heat. Most of the energy released by the sun is either intercepted or deflected away from the earth's surface, leaving less than 2000 BTU/SF-day to impinge on a horizontal surface during a clear summer day, in California. Without any form of concentration, the temperature generated by this insolation is, at most times, less than 160˚F (i.e., sol-air temperature). While such diluted energy may be perfectly adequate for residential hot water services and most space heating systems, it is totally inadequate for the majority of industrial applications.
2. Solar energy is only available for a portion of each 24-hour day. In most regions useful solar energy is limited to no more than 8 to 12 hours on a clear day, depending on the season. Also, clouds diffuse and therefore further dilute solar radiation to an extent that can render it almost useless for collection purposes. Therefore, in view of the discontinuity and unreliability of solar

energy, all solar systems require heat storage facilities and many require conventional back-up provisions.

3. The collection of solar energy is relative expensive. A typical active solar system, including collector, heat storage unit, facilities for the transmission of the collected heat, and some form of backup heating, costs more than a comparable fossil fuel heating system. However, government funded incentive programs combined with the rising cost of electricity provided by local utility companies are increasingly making solar systems a more competitive alternative for residential buildings.

There are several factors that must be considered in the decision on whether or not to adopt a solar energy approach in building design. First, although solar energy is not suitable for satisfying all energy needs, it may still be most appropriate for some applications. In fact, the low-quality nature of solar energy is not a deterrent for water and space heating applications where temperatures seldom exceed 150˚F. Therefore, it was postulated in the 1970s that solar energy could easily account for more than 5% of the total annual energy consumption in the US by 1990, if it were to be confined to that application alone. Second, even if solar energy systems are more expensive than conventional systems, we still have to consider the sun to be an attractive non-polluting source of heat.

Third, both advances in photovoltaic (PV) technology leading to increased PV-cell efficiency at decreased cost and, in particular, the government mandated requirement for public utility companies to accept and reimburse building owners for surplus electricity generated by their photovoltaic units have made solar electricity generating systems an attractive proposition. The ability to connect the small-scale PV-based system of a home to the large-scale public utility grid has solved the vexing need for a backup source of electricity, while adding the highly desirable incentive of receiving credit for any surplus electricity that might be generated.

Finally, the arguments for and against solar energy cannot be based purely on economic criteria. The fact is that the world is rapidly depleting all available fossil fuel sources and therefore, we need to explore the potential applications of solar energy and other non-fossil fuel sources, such as wind energy and geothermal energy, regardless of whether or not these alternative sources are immediately cost competitive.

5.1.1 Solar Energy Incentive Programs

In the US solar incentive programs are offered at both the state and federal government levels, with some additional local government and utility company programs.

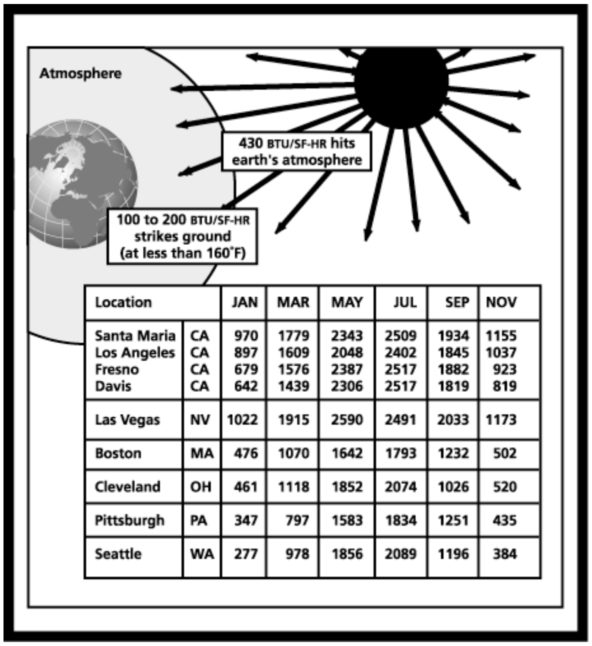
Federal Investment Tax Credit (ITC): Allows homeowners and businesses to deduct a percentage of their solar costs from their federal taxes. The ITC program was established in 2005 with an initial rate of 30%. This rate has been progressively reduced to 26% in 2020, 22% in 2023, and now stands at 10% for 2024 and beyond.

State government incentives: Many states offer additional tax credits, rebates, and/or performance-based incentives to encourage the installation of solar energy systems. Most states mandate utility companies to accept and reimburse homeowners and businesses for any surplus electricity generated by their solar PV systems (referred to as *Net Metering*).

Local incentives: Some local municipalities and utility companies offer rebates, grants, and other incentives for solar installations. Prevalent among these are property tax exemptions for the added value to a home due to a solar system. This means that the increased value of a home due to a solar system will not increase the annual property tax.

5.1.2 Availability of Solar Energy

While the latitude of the site, the month of the year and the time of day are fundamental factors governed by the geometry of the sun's path and the inclination of the earth that determine the amount solar radiation available, there are other less predictable factors such as cloud conditions that need to be taken into account.



Location		JAN	MAR	MAY	JUL	SEP	NOV
Santa Maria	CA	970	1779	2343	2509	1934	1155
Los Angeles	CA	897	1609	2048	2402	1845	1037
Fresno	CA	679	1576	2387	2517	1882	923
Davis	CA	642	1439	2306	2517	1819	819
Las Vegas	NV	1022	1915	2590	2491	2033	1173
Boston	MA	476	1070	1642	1793	1232	502
Cleveland	OH	461	1118	1852	2074	1026	520
Pittsburgh	PA	347	797	1583	1834	1251	435
Seattle	WA	277	978	1856	2089	1196	384

Figure 5.3: Availability of solar energy

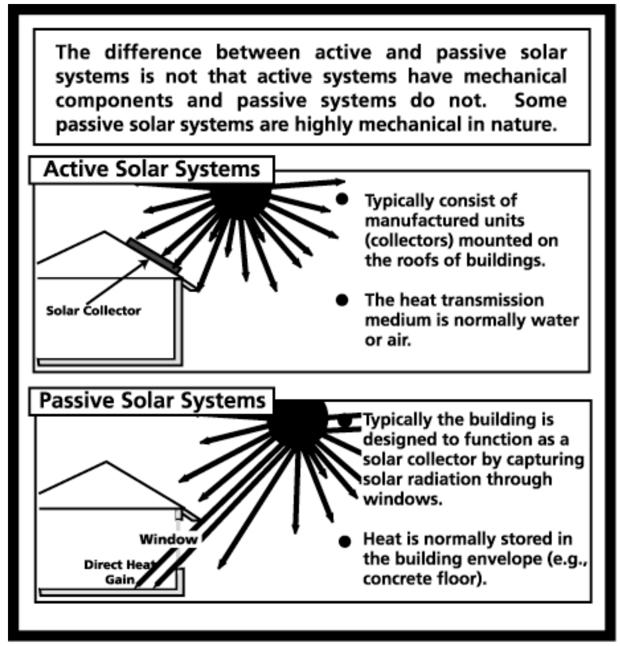


Figure 5.4: Active or passive systems?

As shown in Figure 5.3, about 430 Btu/SF-HR of solar heat is incident on the earth's atmosphere. As it passes through the atmosphere the solar radiation is scattered by ozone, air molecules, water vapor, clouds, dust, and pollution. This scattered radiation can account for 10% to 100% of the total solar radiation that reaches the earth's surface and has to be estimated based on mean (i.e., average) monthly historical data that is collected by government agencies such as the National Climatic Data Center (CDC) of the National Oceanographic and Atmospheric Administration (NOAA).

If we know the mean monthly solar radiation on a clear day (I_{Atm} Btu/SF-day) and the mean percent sunshine (P%) for a particular latitude, then the average solar radiation on a horizontal surface (I_{Avg} Btu/SF-day) can be calculated by the formula:

$$I_{Avg} = I_{Atm} \times (0.30 + (0.65 \times P / 100)) \text{ Btu/SF-day} \quad \ldots\ldots\ldots\ldots (5.1)$$

where: the coefficients 0.30 and 0.65 account for the ratio of diffuse and direct solar radiation, so that on a cloudy day (i.e., P = 0) we can still count on receiving 30% of the clear day radiation (I_{Atm} Btu/SF-day).

This formula (Anderson 1976 (61)) accounts for the available diffuse radiation on cloudy and partly cloudy days. While the two coefficients (i.e., 0.30 and 0.65) vary with climate, location and surface orientation, their variation is not sufficiently severe to result in significant errors. For example, if the mean monthly solar radiation in April is 1700 Btu/SF-day and the mean percent sunshine is 64% for a particular latitude then the average solar radiation (I_{Avg} Btu/SF-day) for design purposes would be:

$$I_{Avg} = 1700\ (\ 0.30 + (\ 0.65\ x\ (\ 64\ /\ 100\ )\ )\ = 1700\ (\ 0.30 + 0.416\ ) = 1217 \text{ Btu/SF-day}$$

Since surface orientation such as horizontal (for a roof or skylight) and vertical (for a window) is a significant factor in determining the incident solar radiation (I_{Avg} Btu/SF-day), tables typically provide separate columns for horizontal and vertical (by orientation) clear sky solar radiation values.

5.2 Two Types of Solar Collection Systems

The simplest way of using solar energy for space heating purposes is to allow the sun to penetrate directly into the building. In this manner, the building acts as a solar collector, by absorbing solar radiation when it needs heat and rejecting it when no heat is required. Such solar systems are known as passive or direct systems, not because they do not incorporate any mechanical components (in fact they often do), but because they rely totally on the passive absorption or rejection of solar radiation (Figure 5.4). To date, passive solar systems have been particularly successful in mild climates, not subject to prolonged cold winters. It is likely that most applications of solar space heating systems in the single-family residential sector will in time come to rely more and more on passive principles.

Active solar systems typically utilize one or more manufactured collector units, normally located on the south facing side of an inclined roof, to collect heat and transport it either in circulating water or air into the building. This type of solar system is known as an active or indirect system, since it consists of components that do not form an integral part of the building envelope. In view of the low temperatures required for hot water services and space heating, most active solar systems incorporate non-concentrating or flat plate solar collectors. However, virtually all active solar systems require a fairly large heat storage facility, a water pump or air fan, pipes or ducts, controls and valves or dampers.

5.3 Flat Plate Solar Collectors

The most important component of an active solar system is the collector. Of the many types of solar collectors that have been developed in recent years, the flat plate liquid or air collector has found the widest application. As shown in Figure 5.5, a typical flat plate collector consists of a flat metal, plastic, or rubber absorbing plate that is painted black or subjected to a special surface treatment for maximum absorption of the sun's heat. Underneath, or in tubes forming an integral part of the absorber plate, a fluid such as water or air is circulated to transfer the collected heat into the building or storage facility. To minimize the heat lost from the collector and circulating fluid, the underside and sides of the collector are well insulated with a several inches thick layer of insulating material such as polyurethane or polystyrene foam. Finally, one or more layers of glass with interstitial air spaces are placed above the collector plate to reduce the outward reflection of heat and take advantage of the *greenhouse effect*.

The efficiency of a flat plate collector (i.e., the percentage of incident radiation that the unit is capable of collecting) is closely related to the number of glazing layers provided, as well as, the temperature difference between the fluid entering and leaving the collector unit (Figure 5.6). Accordingly, collector efficiencies that are stated independently of the specific temperature differential under consideration may be very misleading.

1. Liquid flat plate collectors are available in many variations. Most utilize water with or without an anti-freeze solution as the heat transfer medium. The liquid typically circulates (i.e., is pumped) in pipes that form an integral part of the absorber plate. Problems associated with liquid flat plate collectors are related to leakages, corrosion, freezing, and the relatively high cost of the necessary plumbing work.
2. Air flat plate collectors are also available in many forms. All utilize air as the heat transfer medium, which is blown by fans through one or more ducts located underneath the absorber plate. Advantages of air collectors include freedom from freezing and corrosion, as well as lower maintenance costs. However, these advantages are offset by the relatively large duct size and electricity requirements of the fan, necessary for the transfer of the air from the collector unit to the building interior or heat storage facility.

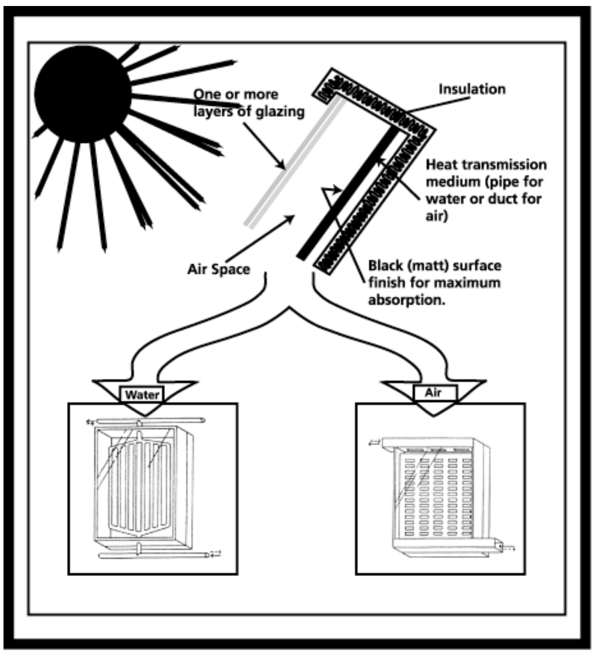


Figure 5.5: Water and air collectors

Collector Type (based on construction)	Typical Temp. (°F)	Efficiency (%)
No insulation and no glazing (black garden hose)	90°F	20%
No glazing (but insulated) (insulation)	130°F	30%
Single glazing (and insulated) (glazing, insulation)	160°F	50%
Double glazing (and insulated) (glazing, insulation)	180°F	60%
Triple glazing (and insulated) (glazing, insulation)	212°F (boiling)	70%

Figure 5.6: Typical collector efficiencies

The choice between an air or water flat plate collector will require consideration of the nature of the intended application, as well as the ambient climatic conditions in respect to the likelihood that freezing conditions may occur in winter. Water collectors are usually favored for domestic hot water services because of the relatively inefficient transfer of heat from air to water.

On the other hand, hot water from a solar collector entering a water storage tank is diffused throughout the water by convection currents. Accordingly, the temperature of the water in the tank may not be high enough to be useful as a hot water service. For example, on a summer day the temperature of the water leaving the solar collector may be as high as 140ºF. However, as this water flows into the storage tank it is quickly diffused throughout the tank, with the result that the temperature of the water may not exceed 100ºF throughout the day. Water at 100ºF is hardly satisfactory for a shower. One way of overcoming this problem, caused by the lack of heat stratification in water, is to use two storage tanks. The hot water from the solar collector is pumped directly into a small tank and from there into the larger tank. With this arrangement a small supply of water at a high temperature (i.e., in the small tank) is available at most times. The disadvantage of this arrangement is the additional cost associated with the requirement for two water tanks and the associated piping.

From an architectural planning viewpoint, the principal feature that distinguishes between solar water and air collectors is the size of the associated pipes or ductwork. While small diameter water pipes can be easily hidden from sight inside walls and vertical plumbing shafts, air ducts are likely to measure at least 6 IN in the smallest dimension making them too wide to fit into a normal wall. This leaves the designer with few options other than to either provide vertical and horizontal casements for the air ducts or to expose the ducts as a special feature that contributes to the aesthetic ambience of the building. In the latter case, the ducts could of course be exposed on either the interior or the exterior of the building envelope.

Water

- Direct heat for hot water service.
- Indirect or direct for space heating.
- Water storage.
- Small pipes.
- Antifreeze or drainage may be required in winter.
- Leakage potential.

Air

- Direct heat for space heating.
- Indirect heat for hot water service.
- Rock storage.
- Large ducts.
- No freezing problems in winter.
- Fewer leakage problems.

Collector Efficiency Factors

1. Operating temperature (difference between T_{Entry} and $T_{Collector}$ is very significant).
2. Degree of thermal insulation.
3. Number of glazing layers.
4. Selective surface finish of collector plate (emissivity of heat absorbing surface).

Figure 5.7: Comparison of water and air collectors and efficiency factors

The ability of a material to store heat is a function of its heat capacity, which is a product of the specific heat and the density.

Storage Material	Specific Heat (BTU/LB-°F)	Density in Container (LB/CF)	Heat Capacity (BTU/CF-°F)
Water	1.00	62	62 (0% void)
Air	0.24	0.075	0.018
Rock*	0.21	130	27 (25% void)
Concrete	0.23	140	32 (0% void)
Brick	0.20	140	27 (5% void)
Scrap Iron	0.12	490	41 (30% void)
Sand	0.19	120	16 (30% void)

* Rock is really gravel (i.e., pebbles).

Figure 5.8: Heat storage potential of common building materials

5.4 Solar Heat Storage Systems

Since solar radiation is not available for all hours of the day it is necessary to store heat for later use. In passive solar heating systems, the heat capacity of the entire building shell can be used as a convenient storage facility. Unfortunately, in the case of active solar systems the heat storage facility is normally looked upon as a self-contained unit that must be accommodated somewhere within, or in proximity of the building. To allow for a storage period of one to two days, the required storage unit can be quite large even for a single-family residential building. Storage unit sizes of 100 to 200 CF (i.e., 750 to 1,500 gallons) for water and 300 to 600 CF (i.e., 20 to 40 TON) for rock are not uncommon. Architectural planning problems and the not insignificant cost associated with heat storage are an incentive for the development of less bulky storage systems.

As shown in Figure 5.8, the heat capacity of a material, such as water or rock, is given by the product of the specific heat and the density (in the container). Although the term *rock storage* is in common use, it actually refers to stone pebbles that typically vary in size from about 0.75 IN to 3 IN depending on the particular design conditions. Therefore, in the case of rock storage the effective density is very much reduced due to the many air pockets between the adjoining rock particles. In other words, 20% to 30% of a rock storage unit may consist of voids, which have negligible heat capacity (i.e., the specific heat and density of air are 0.24 BTU/LB/°F. and 0.075 LB/CF, respectively).

Another approach to reducing the required heat storage volume is to take advantage of the latent heat that is absorbed by materials during a change of phase. For example, Glauber's salt absorbs 100 BTU/LB and paraffin absorbs 65 BTU/LB when they melt at temperatures just above normal room temperature. Although these materials are more expensive and there are problems associated with their typically imperfect re-solidification, desiccant beds can be used effectively in hot humid climates to extract moisture from the air stream. The resultant reduction in relative humidity can result in a significant improvement of the thermal comfort conditions inside the building.

A further problem associated with such systems is that following passage through the desiccant the temperature of the outlet air stream has usually increased by 40°F to 60°F (i.e., exhaust temperatures of 100°F are common), and consequently must be cooled. Without such cooling the effectiveness of the desiccant system is greatly reduced. Possible remedies include the incorporation of a passive heat sink in the desiccant system and the use of a sensible cooling system such as heat exchangers connected to a roof pond. A cooling system that utilizes ambient air may be feasible during the nighttime if the temperature consistently drops to around 80°F.

One or two-bed systems are typically used. One-bed systems are suitable for conditions where the daytime load is low and beds can be regenerated by solar radiation. Otherwise, the one-bed system has to be regenerated during the high solar radiation period of the day, during a 24-hour cycle. Such systems are more suitable for inland regions where daytime dew points are relatively lower. In two-bed systems each bed operates in opposing and alternating cycles of 12 hours of adsorption and three hours of regeneration.

Currently, water and rock (i.e., pebbles) constitute the most popular solar heat storage materials for active solar systems.

1. Water is readily available in the quantities required for heat storage; it is cheap and it has a high heat capacity of 62 BTU/CF/°F (Figure 5.8). As a rule of thumb, approximately 1 to 10 gallons of water are normally required per square foot of solar collector. Water has the advantage of not requiring a heat exchanger when used in conjunction with liquid flat plate solar collectors for a typical residential hot water service. Furthermore, the circulation of water uses less energy than the circulation of air with comparable heat content, and piping is conveniently routed to remote places and around sharp bends. On the other hand, water storage tanks are subject to leakage, freezing, and corrosion, as well as a relatively higher initial installation cost.

   A typical water storage facility is shown in conjunction with a liquid flat plate collector system in Figure 5.9. The coolest water from the bottom of the tank is pumped through the collector where it is heated and then returned to the top of the tank. The warmest water at the top of the tank is circulated directly through baseboard radiators or heating panels inside each room.

Due to convection currents, the temperature difference between any two points in the water tank is seldom more than 25°F. This is a disadvantage, since no appreciable heat stratification can be maintained in the tank.

2. Rock storage is most commonly used in conjunction with active air solar systems. Pebble beds or rock piles normally require two-and-one-half times the volume of an equivalent water storage tank. The sizes of typical pebbles range from 0.75 IN to 3 IN in diameter, and the preferred rock type is of the igneous variety.

   The smaller the pebble size, the greater the resistance to air flow, requiring larger fans and more electric power. A typical rock storage facility is shown in conjunction with and air flat plate collector system in Figure 5.10. During the day, while the sun is shining, hot air is blown from the collector through ducts into the top of the rock storage unit. There, the heat is quickly absorbed by the pebbles leading to a high degree of heat stratification. At night, the cycle is reversed, so that air is blown from the hottest section of the storage unit into the rooms to be heated.

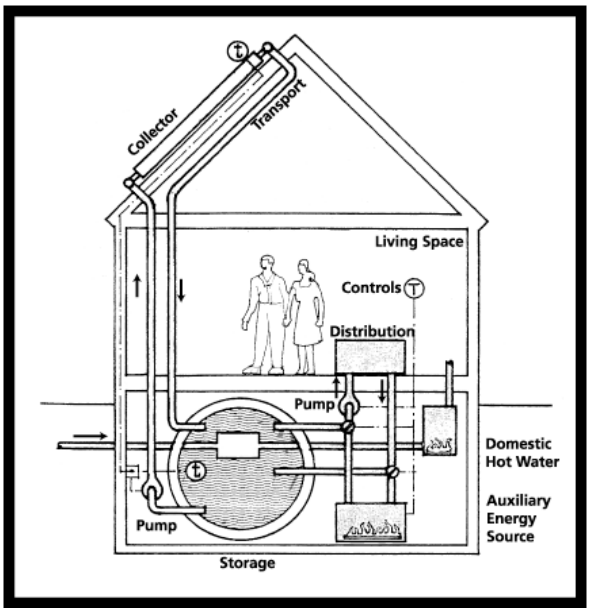


Figure 5.9: Solar water system components

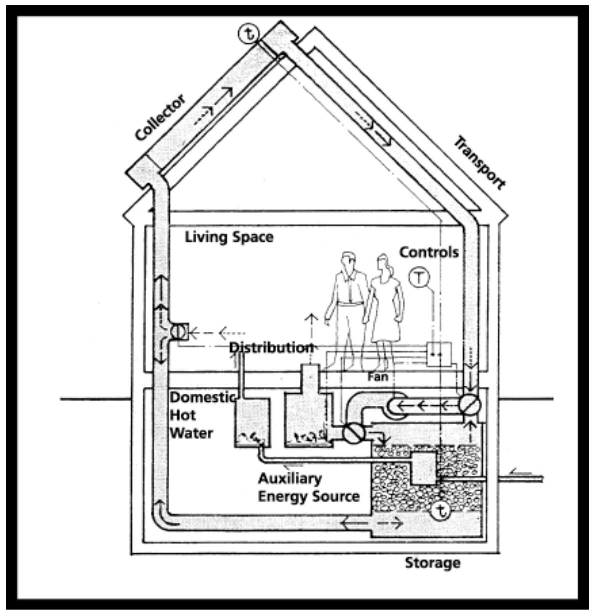


Figure 5.10: Solar air system components

Every heat storage system, whether air or water, requires a large amount of thermal insulation. Thermal resistance values in the range of R20 to R30 (i.e., 3 IN to 5 IN of polyurethane foam) are recommended, depending on the location of the storage tank or rock container. Naturally, all pipes and ducts must be equally well insulated, to minimize the heat losses from the solar system as a whole.

5.5 Sizing a Solar Hot Water Service

As a rule of thumb, under favorable weather conditions, we would expect approximately one square foot of a single glazed solar collector to heat one gallon of water from a mains temperature of 60°F to about 120°F, per day. More accurately the required collector area (A) for a domestic hot water service is given by:

$$\mathbf{A = 8.34 \times W\,(T_H - T_C) / (I \times E / 100)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(5.2)}$$

where:
- A = required collector area (SF)
- W = total hot water required per day (GAL)
- T_H = temperature of hot water (ºF)
- T_C = temperature of cold water (ºF)
- I_{Avg} = daily insolation at collector tilt (BTU/SF)
- E = collector efficiency (%)
- 8.34 Btu = heat required to raise the temperature of 1 gallon of water by 1°F

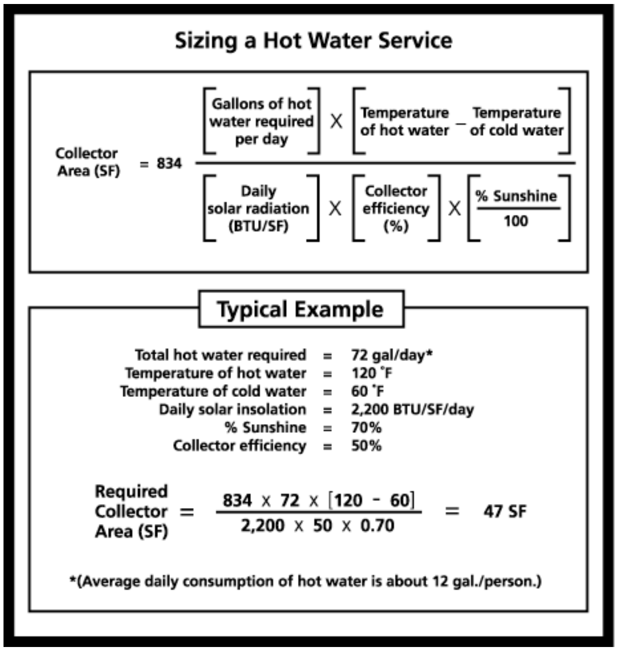


Figure 5.11: Sizing a solar hot water system

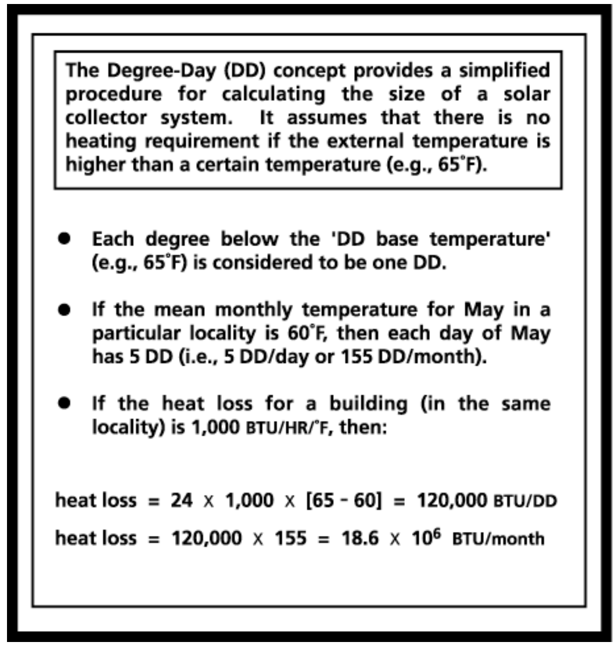


Figure 5.12: The Degree-Day concept

Currently, in the US, the average daily consumption of hot water is about 12 gallons per person. An example of the application of equations 5.2 is shown in Figure 5.11.

Another example that also applies equation 5.1 to determine a more conservative value for the available solar radiation is shown below.

Allowing for a storage capacity of two days, a typical family of three would require 72 gallons (i.e., 2 x 3 x 12 = 72) of water to be heated by solar radiation. Assuming an average daily insolation of 2,200 BTU/SF during the coldest winter month, 74% sunshine (i.e., allowing for clouds) and a collector efficiency of 40%, the available solar radiation (I_{Avg} Btu/SH-day) on the basis of equation (5.1) becomes:

$$I_{Avg} = I_{Atm}\,(0.30 + (0.65 \times P / 100))\ \text{BTU/SF-day}$$
$$I_{Avg} = 2200\,(0.30 + (0.65 \times 74 / 100))$$
$$I_{Avg} = 2200\,(0.30 + 0.481)$$
$$I_{Avg} = \mathbf{1718\ BTU/SF\text{-}day}$$

Using equation (5.2), the required solar collector area (A SF) becomes:

$$A = 8.34 \times W\,(T_H - T_C) / (I_{Avg} \times E / 100)\ \text{SF}$$
$$A = 8.34 \times 72\,(120 - 60) / (1718 \times 40 / 100)$$
$$A = 36028.8 / 687.2$$
$$A = \mathbf{52.5\ SF}$$

5.6 The Degree-Day Concept

The Degree-Day (DD) concept serves as a convenient and useful measure of the severity of a climate. While it is most commonly applied to determine heating requirements, it can be equally well applied to cooling requirements in warmer climates. It is based on the concept that there exists an equilibrium external temperature at which no supplementary heating (or cooling) will be required inside a building. For the same climate this base temperature is likely to be slightly different for assessing the heating and cooling requirements.

The normal DD base temperature for heating is 65ºF. If another base temperature is chosen then this is always indicated in the calculations. It is assumed that no heating will be required if the external temperature is above the DD base temperature. Each degree below the base temperature is considered to be one DD. Therefore, if the mean temperature during the month of November in a particular region is 56ºF, then this region will have 270 DD for that month (i.e., (65ºF – 56ºF) x 30 days = 270 DD). The calculation of an actual heating requirement in BTU/DD is shown in Figure 5.12. It simply requires the estimated heat loss in BTU/HR-ºF to be multiplied in turn by the DD/day (i.e., 9 DD/day in the above example) and the number of hours during which this heat loss is expected to persist on a particular day. This calculation tends to lead to conservative results since it assumes that the estimated heat loss (BTU/HR-ºF) applies throughout the entire 24-hour period of a day. Nevertheless, it is commonly accepted as a sufficiently accurate measure of the size of a solar collector facility.

5.7 Sizing a Solar Space Heating System

The principal factors involved in determining the solar collector area and the heat storage volume required for solar space heating are shown in Figures 5.13 and 5.14, respectively. However, by using short-cuts that ignore several secondary factors these examples provide only very approximate results. A more accurate determination of the required size of the collector area and heat storage volume would involve the following steps:

1. Determine the net heat loss that will be experienced by the building each month taking into account the outdoor design temperature, the desired indoor air temperature, the heat loss through the building shell (i.e., roof and skylights, external walls and windows, and floor), as well as the heat gain by direct solar radiation through windows and skylights.
2. Assuming that the solar collector panels will have a near optimum tilt angle, establish the amount of solar radiation that can be collected each month. This will depend on the latitude of the site location, the percentage of sunshine, as well as the efficiency of the collector.
3. Decide on the percentage of the total heating requirements to be catered for by solar energy. While this percentage will be the same for each month, the deficit heat that must be supplied by an auxiliary heating facility will be different for each month. It is likely to be zero for some summer months. In fact, in the case of warm and even temperate climates no solar heating at all is likely to be required for some summer months.

4. Using the month with the largest net heating load as a basis, reduce this value to the percent of heating to be provided by solar energy, and calculate the solar collector area required according to equation (5.3).
5. Decide on the number of days for which solar heat is to be stored, select the heat storage medium, and calculate the volume of the storage facility using equation (5.4).

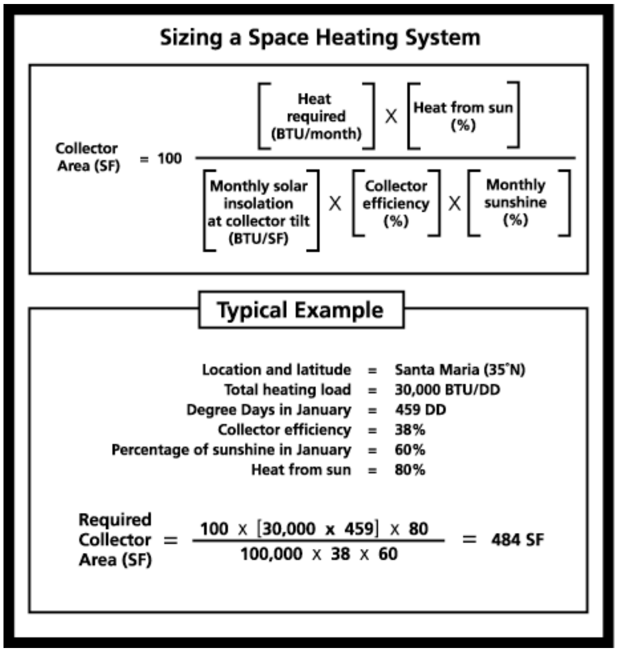


Figure 5.13: Sizing a Solar Heating System

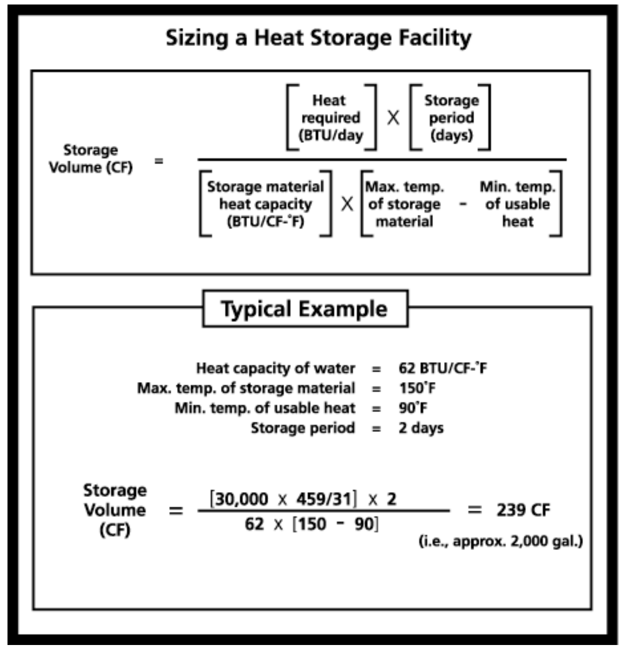


Figure 5.14: Sizing the heat storage facility

$$\mathbf{A = Q_{Net} \times (P / 100) / (I_{Avg} \times (E / 100)}\ \text{SF} \quad \ldots\ldots\ldots\ldots \quad \mathbf{(5.3)}$$

where:
- A = required collector area (SF)
- Q_{Net} = largest net heating requirement of all months (BTU/day)
- P = percentage of heat to be supplied by solar energy (%)
- I_{Avg} = monthly insolation at collector tilt (BTU/SF-day)
- E = collector efficiency (%)

Also, the required heat storage volume (V CF) for a storage period of D days, is given by:

$$V = \mathbf{Q_{Solar} \times D / (H_C \times (T_S - T_U))} \quad \ldots\ldots\ldots\ldots \quad \mathbf{(5.4)}$$

where:
- V = required heat storage volume (CF)
- Q_{Solar} = solar heat collected on design day (BTU/day)
- D = storage period in days
- H_C = heat capacity of storage material (BTU/CF-˚F)
- T_S = maximum temperature of heat storage material (˚F); - normally 130˚F to 160˚F.
- T_U = minimum temperature of usable heat (˚F); - 90˚F to 110˚F.

Due to the relatively large volume of storage required, architectural planning problems encountered in accommodating this storage volume, and the cost involved, storage periods of one to two days are normally considered adequate.

For a well-insulated 3,500 SF building located in Atlanta, Georgia with a window area equal to 15% of the external wall area, a skylight area of 20 SF, and a ceiling height of 9 FT, steps 1 and 2 of the more detailed solar space heating design process outlined above would produce the following the monthly heating load and solar collector area results:

Month	Outdoor Design Temperature	Conduction Heat Loss Daytime (Btu/day)	Conduction Heat Loss Nighttime (Btu/night)	Radiation Heat Gain (Btu/day)	Net Heat Loss (Btu/day)	Available Solar Heat (Btu/SF-day)	Minimum Collector Area
JAN	40 °F	-230,766	-323,075	+93,836	-460,005	1,045	734 SF
FEB	47 °F	-196,580	-275,212	+111,300	-360,492	1,005	598 SF
MAR	54 °F	-132,478	-185,471	+118,351	-199,598	790	421 SF
APR	62 °F	-127,001	-95,728	+127,001	-95,728	520	307 SF
MAY	71 °F	0	0	+133,258	0	371	0 SF
JUN	77 °F	0	0	+129,056	0	334	0 SF
JUL	81 °F	0	0	+121,173	0	349	0 SF
AUG	80 °F	0	0	+121,788	0	499	0 SF
SEP	73 °F	0	0	+131,382	0	829	0 SF
OCT	64 °F	-136,953	-77,777	+136,953	-77,777	1,108	117 SF
NOV	54 °F	-141,026	-197,437	+115,657	-222,806	1,156	321 SF
DEC	45 °F	-213,676	-299,146	+87,040	-425,782	1,032	688 SF

The largest net heat loss of 460,005 Btu/day occurs in January when the available solar radiation is 1,045 Btu/SF-day. For 100% solar heating with a double-gazed well-insulated collector that has a base efficiency of 60%, the required solar collector area would be 734 SF, which is quite large. For 75% solar heating the required collector area would reduce to a perhaps more acceptable size of 550 SF.

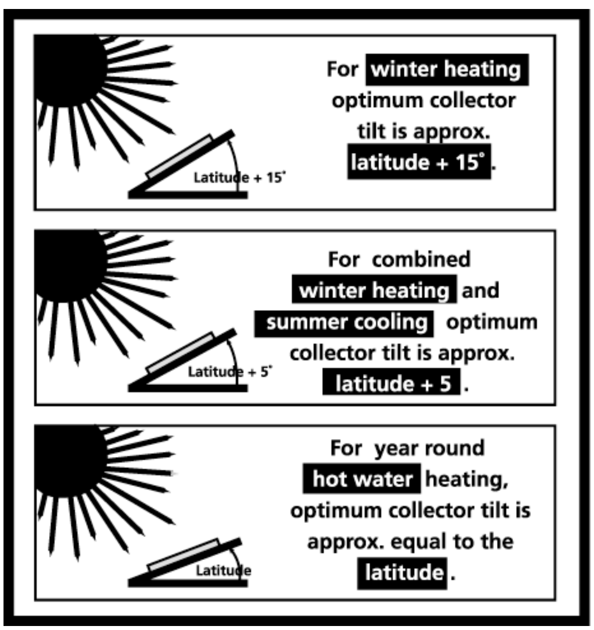


Figure 5.15: Optimum collector slopes

- √ Approximately 1 to 10 gallons of water are normally required per SF of collector area for heat storage.
- √ Rock heat storage is approximately 2.5 times larger in volume than water storage.
- √ Pebble sizes in rock storage normally range between 0.75 to 3 inches.
- √ Heat storage facilities require substantial thermal insulation (R20 to R30, i.e., 3 to 5 inches of polyurethane foam).
- √ Under good weather conditions 1 SF of single-glazed solar collector should be able to heat 1 gallon of water from 60° to 120°F.

Figure 5.16: Rules of thumb

Ideally, the angle between the incident rays of the sun and a flat plate solar collector should always be 90º. However, since in our view (i.e., as it appears to us from the earth) the position of the sun continuously changes in both altitude and bearing from sunrise to sunset, to maintain this optimum 90º angle would require the collector to track the sun. To date such tracking devices have been considered to be too expensive for flat plate solar collectors. In other words, the efficiency (i.e., lack of efficiency) of a flat plate collector simply does not warrant the sophistication and expense of a tracking mechanism. On the other hand, such mechanisms are considered appropriate and have been used successfully with concentrating solar collectors. In these collectors the collection surface is typically concavely curved and highly reflective (e.g., like a mirror) to focus the sun's rays onto a target at the focal point.[1] These concentrating collectors are much more expensive than flat plate collectors due to the cost associated with the production of a relatively large, curved, mirror like surface. To fully exploit these higher production costs, it becomes important to maintain an optimum profile angle between the curved collector mirror and the sun. This justifies the addition of a tracking mechanism.

In the case of a flat plate collectors (i.e., fixed in position) we select an orientation and slope that optimizes the exposure to the sun. The optimum orientation is direct south (for the Northern Hemisphere and direct north for the Southern hemisphere) and the optimum slope is dependent on the latitude of the location and whether the solar heat is being collected for use year-round or just in winter. For example, a solar hot water service would need to collect solar energy throughout the year, while a solar space heating facility might be needed only during the winter months. As shown in Figure 5.15, the optimum collector angles recommended for these different applications differ by as much as 15º.

5.8 Integrating Building Structure and Heat Storage

An interesting concept for combining the structural support system of a residential building with the storage requirements of a typical active solar heating system was investigated during the mid 1970s in a full-size test building constructed by students in the School of Architecture and Environmental Design at the California Polytechnic State University (Cal Poly), San Luis Obispo, California.

The building incorporates an innovative fluid-supported structure, consisting of a central 5 FT diameter column fabricated from 18-gauge galvanized steel sheeting and filled with a mixture of sand and water. It is the dual function of the sand-water mixture to support the building loads and act as a convenient heat store for solar energy collected at roof level (Figure 5.17).

Structurally, the column is classified as a thin-walled cylindrical shell, which is subject to local buckling (i.e., crinkling or folding of the thin column wall) under excessive vertical loads. The resistance to buckling of such a column can be very much increased by pressurizing the column interior with a fluid, such as air, water or sand. The initial structural concept called for water to be used as the pressurizing medium. Unfortunately, two attempts to render the column waterproof by inserting a plastic bag inside the column failed. Each time the plastic bag developed a leak either before or during the filling operation. Therefore, it was decided to substitute sand for water as the pressurizing medium. Although sand is not commonly described as a fluid, it does display a number of fluid properties. When a bucket of dry sand is poured onto the ground, it forms a heap with sides sloping at an angle of approximately 45˚, governed by the friction between individual sand grains. This indicates that sand has limited shear strength and therefore transmits a proportion of superimposed vertical loads sideways. Accordingly, the sand in the building column produces pressure on the inside surface of the column wall, thereby resisting the formation of local buckles

[1] The alternative approach to a curved collector mirror is a concentrating lens that focuses the sun's rays onto a target. In this case the high cost of the concentrating collector is derived from the cost of the lens.

(i.e., wrinkles or folds) in the column wall. In addition, the sand has the ability to directly support the vertical load of the building as long as it is contained by the column wall.

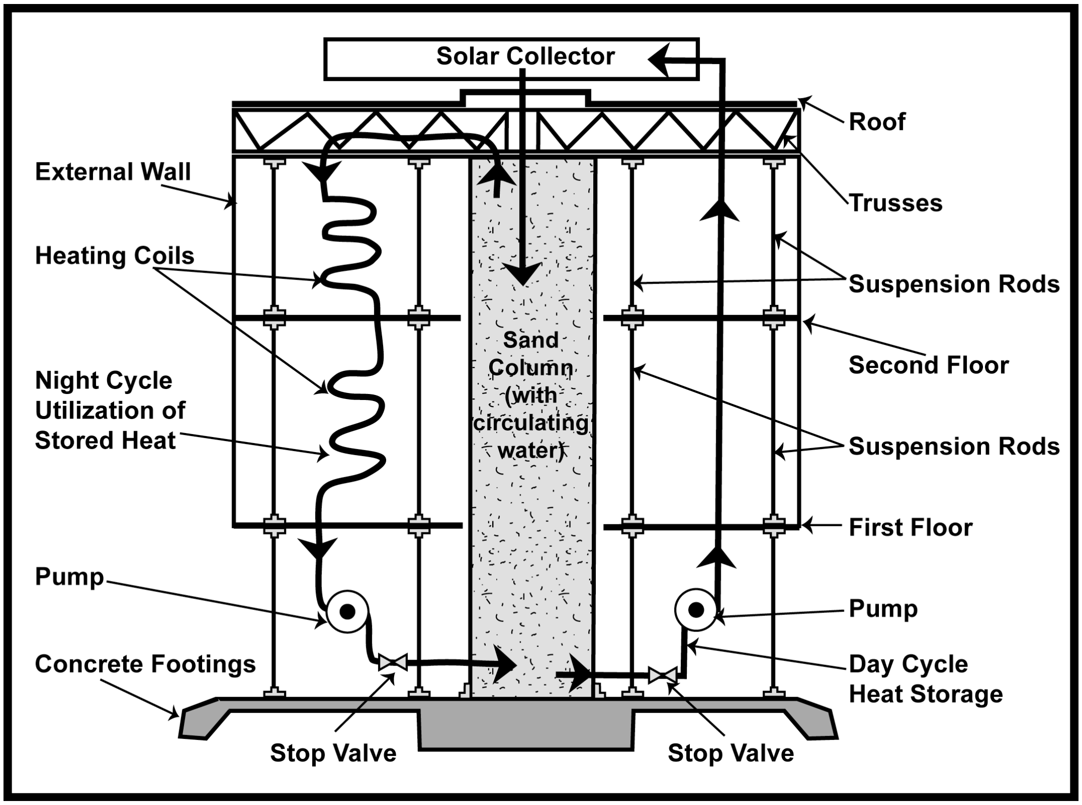


Figure 5.17: System diagram of the sand column concept

The column wall is welded at all joints and sealed top and bottom with circular mild steel plates (i.e., 0.25 IN thick). At roof level, eight open-web steel joists or trusses are welded to the top column plate. The trusses are fabricated from mild steel angles (i.e., 2 IN by 3 IN by 0.25 IN thick) that cantilever approximately 10 FT out from the central column.

The suspended floors are approximately 22 FT in diameter and of octagonal shape. Each floor consists of eight wedge-shaped prefabricated panels constructed with 1-3/4 IN thick rigid polystyrene foam sheets sandwiched (i.e., glued) between two layers of 3/8 IN plywood sheets. Each floor panel is provided with a frame of standard 2 IN by 4 IN timber beams laid flat around the perimeter. Individual panels were joined by gluing together overlapping plywood skins. The final panel thickness is 2.25 IN. The floors are suspended from roof level by means of 16 mild steel suspension rods, attached to the radial roof trusses and prestressed to the footings by means of turnbuckles. The rods are of 5/8 IN diameter.

The solar collector consists simply of a 1,300 FT long, 3/4 IN diameter, black polyethylene hose laid onto the roof surface in the form of a spiral and glazed over with a single layer of translucent tedlar coated panels. With an estimated efficiency of 35%, the 330 SF solar collector is capable of providing 100% of the space heating requirements in January, while the central sand-column has a heat storage capacity of five days.

The principal advantages of this type of fluid-supported building are related to the ability to integrate the structural and environmental functions into one efficient component, thereby obviating the need to accommodate a separate, large heat storage unit. Moreover, the structural efficiency of the fluid-supported column itself can lead to additional cost savings, particularly on sloping sites.

5.9 Passive Solar Systems

Active solar systems, whether flat plate or concentrating collectors, are typically manufactured units that are attached to the external envelope of a building. A much more elegant approach is to design the building itself as a solar heat collector. This is the objective of a passive solar system. Ideally, the design of a passive solar system should allow the building to not only collect solar energy, but also to store it and to distribute it when needed. Unfortunately, in practice this ideal objective is difficult to achieve. The kinds of problems encountered by the designer include difficulties associated with controlling the penetration of the sun into the building and the even distribution of the collected heat within the interior spaces.

Four principal passive solar approaches will be discussed, namely: Direct Gain systems; Trombe Wall systems; Sunspace systems; and, Roof Pond systems (Figure 5.19). Of these only one, the Roof Pond system, is capable of winter heating and moderate summer cooling. This makes the Roof Pond system a particularly attractive proposition for temperate climates. The other three approaches, apart from providing little (if any) relief in summer suffer from the compounding problem of potentially allowing excessive heat to enter the building spaces during the summer months.

Each of the four passive solar system approaches described below includes an example with a summary of key design parameters based on the geographical location of a hypothetical building site (i.e., Los Angeles, California). The values shown for these parameters are only very approximate estimates, extrapolated from government funded research conducted by the American Institute of Architects (AIA) Research Corporation and published in book form in 1978 (Regional Guidelines for Building Passive Energy Conserving Homes) and 2003 (Solar Dwelling Design Concepts).

Fundamental to the approximate design process employed in the examples is the division of the US into 17 regions (Figure 5.18) based on five climatic determinants, namely: mean monthly high and low temperatures; relative humidity plotted on a psychrometric chart in combination with mean high and low temperatures; mean wind speeds and primary directions; mean percent sunshine; and, Degree-Days for heating and cooling.

For example, a narrow coastal strip in Southern California around greater Los Angeles, with its mild climate cooled mostly by on-shore winds, low relative humidity that makes even temporary wind changes that bring hot desert air from inland areas quite tolerable, and very moderate winter temperatures, is designated as Climate Region 17. In stark contrast Climate Region 1, which includes most of Connecticut and New England, is characterized by cold temperatures that often drop below freezing in winter, snow and winds in winter that add an uncomfortable chill factor, and milder summers that may include a few days of hot humid conditions. However, since the mean percent sunshine is above 50% year-round and close to 60% for all months except November and December, there are opportunities for supplementary solar heating even in this colder region. Climate Regions 8 and 9 that stretch from the Atlantic Coast in South Carolina (Charleston) to the Mississippi Valley in Arkansas (Little Rock) have hot, humid summers and cold winters that become more severe with greater distance from the coast. Direct solar heating in winter and natural cross-ventilation cooling in summer are potential passive energy conservation strategies.

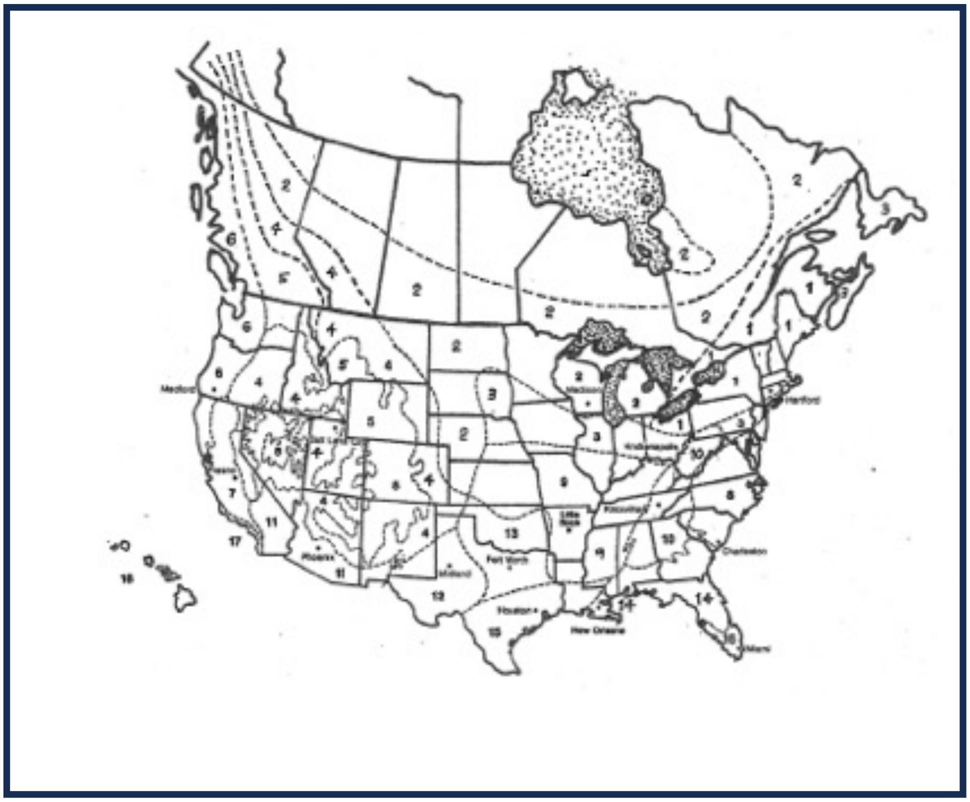


Figure 5.18: Climate Regions

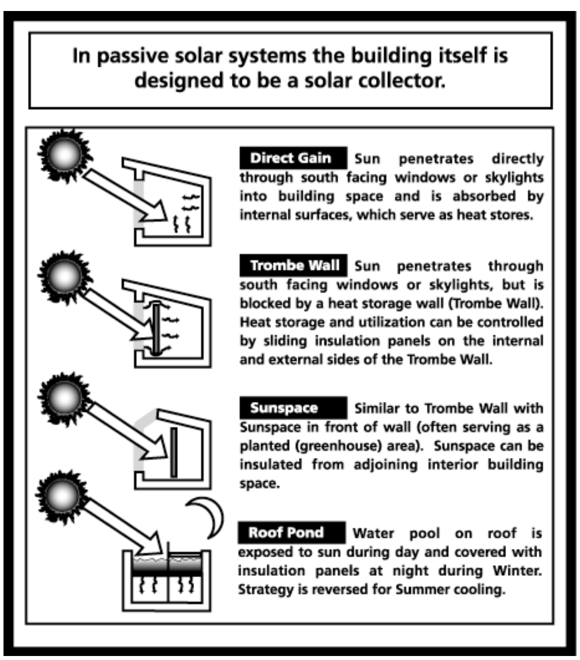


Figure 5.19: Typical passive solar systems

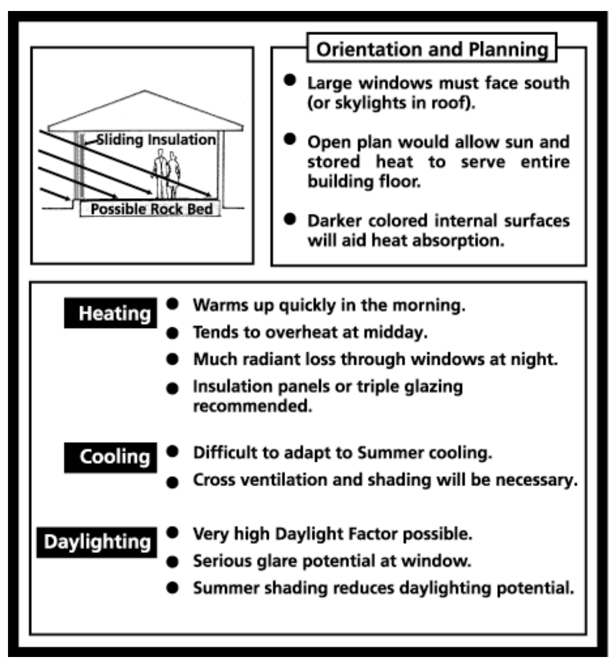


Figure 5.20: The Direct Gain system

5.9.1 Direct Gain Systems

Direct Gain passive solar systems rely largely on the greenhouse effect for trapping heat in the building. There are many parts of a building such as south-facing windows (Figure 5.20), roof lights and even attached greenhouses that may be used as built-in solar heat traps. To avoid overheating of the building space, care must be taken to facilitate the absorption of heat by materials with good heat capacities, such as concrete, brick, tile or stone floor and walls. If well-designed, these masonry elements will have just the right amount of heat capacity to maintain a thermally comfortable building environment during the night.

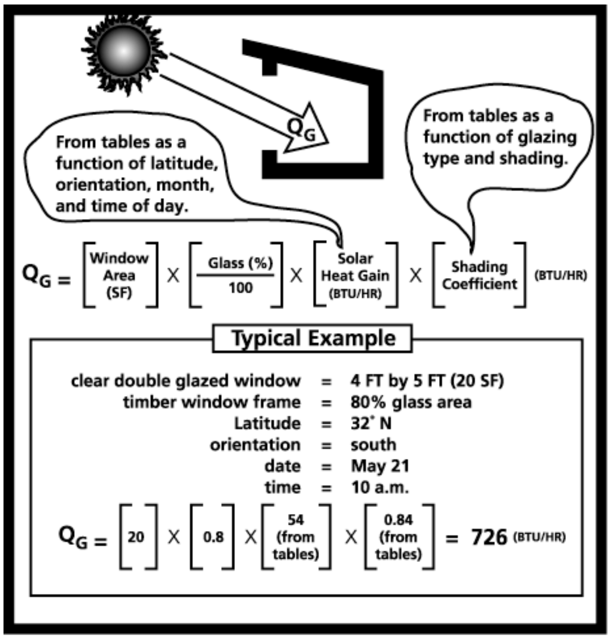


Figure 5.21: Solar heat gain through glass

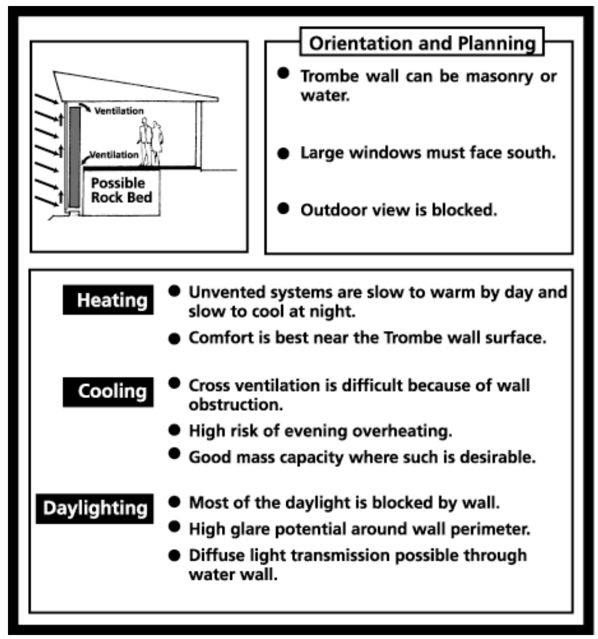


Figure 5.22: The Trombe Wall system

Also, there is a need for a fairly open plan floor layout so that the solar heat will be well distributed throughout the building. Internal subdivision of the building space into several smaller rooms will tend to concentrate the collected heat in those spaces that directly adjoin the south-facing windows.[2]

Direct Gain systems respond quickly to external solar radiation conditions. On the positive side this facilitates the warming of the building interior in the morning after a cool night. However, on the negative side, this also tends to lead to overheating by midday and may require the provision of some shading mechanism (e.g., external solar shades and/or internal blinds) to control the amount of solar heat penetration. In other words, Direct Gain systems are difficult to adapt to summer conditions in climatic regions where cooling will be required. Under such conditions the principal control mechanisms available to the designer are restricted to:

1. Reduction of the size of the south-facing openings. This requires careful calculation of the actual solar heat gain through a window opening. As shown in Figure 5.21, the solar heat gain through glass (Q_G BTU/HR) can be estimated by applying the following formula:

$$Q_G = A (G_P / 100) \text{ x } Q_R \text{ x } S \text{ BTU/HR} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5.5)$$

where: Q_G = estimated heat penetration into building (BTU/HR)
A = window area including frame (SF)

2 South-facing windows in the Northern Hemisphere and north-facing windows in the Southern Hemisphere.

G_P = percentage of window that is glass (%)

Q_R = solar heat gain (BTU/HR) (from tables as a function of latitude, orientation, month, and time of day)

S = shading coefficient (from tables as a function of glazing type and degree of shading)

2. Provision of movable, reflective insulation panels or blinds that can be applied manually or automatically to the internal surface of the window as a heat shield during the overheated periods of the day.
3. Facilitation of cross-ventilation in much the same manner that this measure is used for cooling in hot humid climates. The degree to which this approach may be successful will depend largely on the prevalence and dependability of natural breezes during the part of the day when overheating is likely to occur.

Example[3]: For an estimated 72% solar heating, a typical Direct Gain design solution for an 1,800 SF (i.e., 60 FT by 30 FT by 9 FT ceiling height) one-story building located in Los Angeles, California is shown below. The floor would be a concrete slab and night insulation would be provided.

south-facing solar aperture window area = 162 SF (9% of floor area)
required width of solar aperture window = 18 FT
required thermal mass floor area = 486 SF (300% of window area)
thermal mass floor thickness = 5 IN
thermal mass heat storage volume = 203 CF
floor area not used for heat storage = 1,314 SF (73% of total floor area)

5.9.2 Trombe System

Trombe wall systems utilize the thermosyphoning concept to circulate the heat stored in a wall or roof structure by means of naturally occurring thermal currents. As shown in Figure 5.22, a heat absorbing wall (e.g., masonry) is placed within a few inches of the inside surface of a window. The surface of the wall facing the window is painted black for maximum heat absorption, and the interstitial air space is vented over the top of the wall into the building space. Note the cold air return located at the bottom of the wall to facilitate the thermosyphoning effect.

The principal disadvantages associated with this passive solar system are related to the blocking of daylight by the Trombe wall itself, the slow response to warming in the morning, the equally slow response to cooling at night, and the difficulties associated with combating potential overheating with cross-ventilation. However, on the positive side, the Trombe wall system provides a high thermal mass capacity in colder climates where the intensity of solar radiation may be limited and the daytime temperatures are relatively low.

Example: Using the same specifications as in the Direct Gain example: For an estimated 72% solar heating system of an 1,800 SF (i.e., 60 FT by 30 FT by 9 FT ceiling height) one-story building located in Los Angeles, California with a brick Trombe wall and night insulation the results would be:

south-facing solar aperture window area = 162 SF (9% of floor area)
required width of solar aperture window = 18 FT

[3] The design process used in this example (and its reuse in Sections 5.9.2 and 5.9.3) is based on the concept of climate regions described in the book Regional Guidelines for Building Passive Energy Conserving Homes produced by the AIA Research Corporation (1978).

required thermal mass wall area = 162 SF (100% of window area)
thermal mass wall thickness = 12 IN
thermal mass wall width = 18 FT
thermal mass wall height = 9 FT
thermal mass heat storage volume = 162 CF

5.9.3 Sunspace System

The characteristics of Sunspace systems (Figure 5.23) are very similar to Direct Gain systems. Differences are related to the nature of the sunspace itself, which serves as the primary heating element of the building. On the one hand, this space can be treated as a greenhouse with attractive plantings that can greatly enhance the character of the building interior. On the other hand, the separation of the sunspace from the other building spaces restricts the penetration of daylight into those interior spaces and also reduces the cross-ventilation potential. Experience has shown that the Sunspace system is prone to more extreme temperature swings then the Direct Gain system and considerable radiant heat losses during the night.

Example: Again, using the same building specifications as in the Direct Gain and Trombe wall examples: For an estimated 72% solar heating system of an 1,800 SF (i.e., 60 FT by 30 FT by 9 FT ceiling height) one-story building located in Los Angeles, California with a Sunspace 20 FT by 15 FT, a concrete wall and night insulation the results would be:

south-facing solar aperture window area = 162 SF (9% of floor area)
required width of solar aperture window = 18 FT
required thermal mass wall area = 324 SF (200% of window area)
thermal mass wall thickness = 6 IN
thermal mass wall width = 36 FT
thermal mass wall height = 9 FT
thermal mass heat storage volume = 162 CF

5.9.4 Roof Pond System

The Roof Pond system invented by Harold Hay under the name of SkyTherm™, is an ingenious concept (Figure 5.24). It overcomes virtually all of the overheating and temperature swings that characterize the other three passive solar design approaches. Its relatively low acceptance to date is not due to any lack of solar performance, but related to an entirely different set of problems. The maintenance requirements related to the need for movable insulation panels and the ultra violet radiation degradation of the clear plastic bags that are required to contain the water on the roof have proven to be strong deterrents within the context of current building practices.

A solar pond is a fairly shallow pool of water, often contained in one or more plastic bags, which can serve both as a solar collector and a heat storage facility. Water at any depth acts as Black Body (i.e., absorbs all incident radiation). The SkyTherm concept utilizes the solar pond principle to collect solar heat during winter days and radiate heat to the colder night sky in summer.

Movable insulation panels are activated by differential thermostats to cover the solar ponds during times when neither heating nor cooling of the water is required. At other times the roof ponds remain exposed to the sun so that they can collect heat. During a typical winter day-night cycle the insulation panels will automatically slide over the roof ponds in the late afternoon (or during cloudy daytime periods) to minimize the loss of heat from the water during the cold night. Then, when the sun rises in the morning and there is sufficient radiation to collect heat the panes slide to one side of the roof (normally over the garage area) to allow the water to collect solar energy. During the summer the day-night cycle is simply reversed. The insulation panels automatically slide over the roof ponds during the day to avoid overheating under intense solar radiation, and slide away from the roof ponds after sunset to facilitate the cooling of the water through nighttime radiation to the relatively cool sky. At sunrise the same cycle is repeated with the insulation panels again automatically sliding over the water bags.

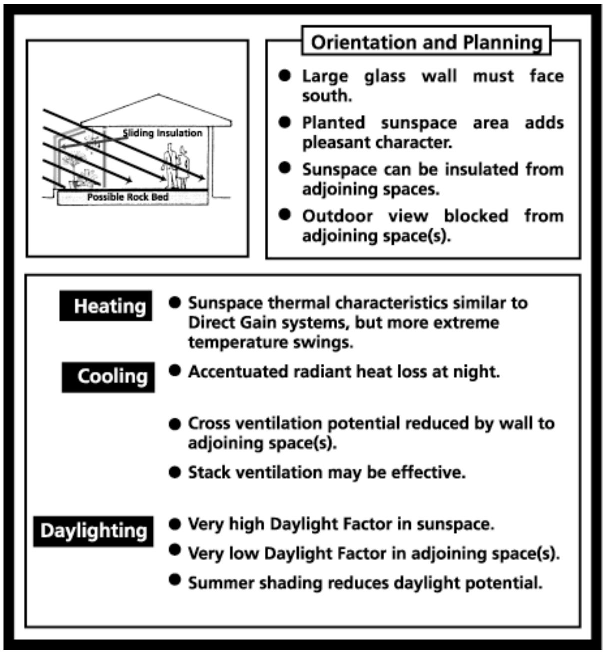


Figure 5.23: The Sunspace system

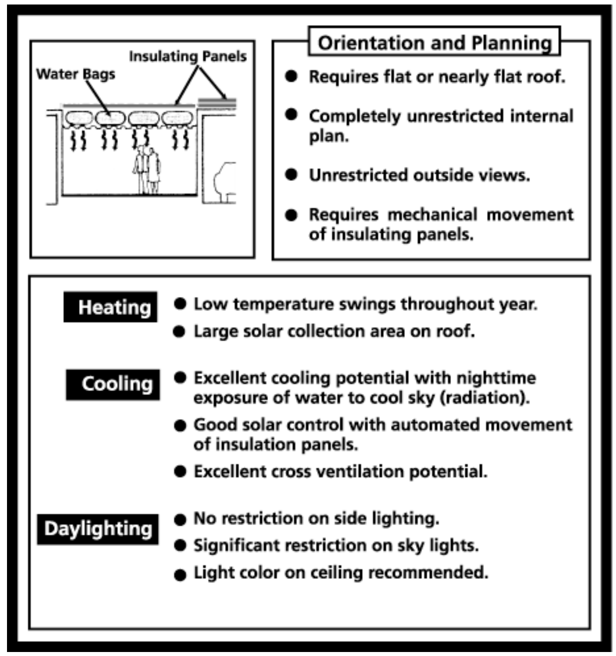


Figure 5.24: The Roof Pond system

The Roof Pond system has several additional advantages apart from its ability to provide both winter heating and summer cooling. First, it does not impose any restrictions on the building plan in respect to orientation, internal layout, or the size and location of windows. Second, the system does not in any way impact the availability of daylight nor does it restrict the provision of cross-ventilation. Third, testing of several full-size structures over extended periods has shown that the Roof Pond system experiences the least temperature swings of any of the passive solar systems. And, this applies to both summer and winter conditions (Hay and Yellott 1970, Hay 1973).

Example: For an estimated 70% solar heating and cooling Roof Pond system of a 2,000 SF (i.e., 50 FT by 40 FT) one-story building located in Los Angeles, California with a water pond that takes up 90% of the roof area, the results would be:

roof pond water area = 1,800 SF (90% of floor area)
roof pond water depth = 8 IN
roof pond water container depth = 12 IN
roof pond water volume = 1,200 CF
roof pond water weight = 74,400 LB (41.3 LB/SF)

5.9.5 Radiative Cooling of Water Ponds

The process by which the body of water on the roof of a passive solar Roof Pond system loses heat during the night is referred to as radiative cooling. In this process objects radiate invisible energy in the form of infrared radiation to cooler surroundings, such as the cooler night sky. Since the radiating water loses heat, it becomes cooler. However, the cooling rate is diminished by the effect of the immediate environment surrounding the roof pond that has been heated by the sun during the day. This effect, referred to as downwelling, increases significantly under even a partially overcast night sky. The balance between the outgoing radiative cooling and suppressive downwelling determines how effective the cooling process of a Roof Pond system will be during a summer night.

5.10 Photovoltaic Systems

Technological advances that are continuing to increase the efficiency of photovoltaic (PV) cells combined with an increasing demand for photovoltaic systems has made the solar production of electricity on an individual building basis an economically desirable proposition. The increase in demand has been driven partly by the rising cost of electricity drawn from the locally accessible power grid and the increasing public awareness of potential threats associated with climate change. However, the ability to connect your PV system to the power grid and thereby obviate the need for batteries to store surplus electricity and at the same time earn a credit for passing that surplus onto the grid has created a major incentive.

Initial installation costs depend on the electric load and the number of sunshine hours per day, but are typically recouped over a payback period of 5 to 9 years. PV systems generally require little maintenance. Cleaning the array panels perhaps once every two years (unless they are located in a very dusty environment) and checking the monitor to ensure that the inverter and associated components are working properly are the only maintenance tasks. The lifespan of a PV array may be as much as 40 years with manufacturers typically offering a 20-year warranty that the array will continue to produce at least 80% of its initial output after this period.

The design sequence for a PV array system involves the following steps:

(a) Determine the electric load of the building (L watt-hrs/day). The Power Budget of a room is calculated as the product of the base Unit Power Density (UPD) prescribed by building codes for the type of room, a Room Factor (RF) that is based on the dimensions of the room, and ranges from 1.00 to 2.00, and a Space Utilization Factor (SUF) that accounts for the ratio of the workstation area to the total floor area of the room and ranges from 0.4 to 1.0.

(b) Select the type of PV cell to determine the efficiency of the PV array in terms of watts/SF (E watts/SF).

(c) Decide on the percent of the electric load to be supplied by the PV system (P%).

(d) Determine the average sunshine hours (S hrs.) for the location of the site (nearest city) in winter and in summer using maps of the US such as those made available by the National Renewable Energy Laboratory (NREL).

(e) Calculate the PV array area (PV_{Area} SF) required for a winter and a summer month:

$$PV_{Area} = (L \times (P / 100) / S) / E \text{ SF} \quad \ldots\ldots \quad (5.6)$$

(f) Calculate the daily electricity generated during a winter month and during a summer month and compare these totals with the daily electric load of the building

(L watt-hrs./day) to determine the typical daily winter and summer generated electricity surplus and/or deficit.

(g) Multiply the typical daily surplus and/or deficit by the number of winter and summer days to determine the annual deficit kilowatt hours that will need to be drawn from the grid and the annual surplus kilowatt hours that will be credited by the utility company.

Example: For a building located in Atlanta, Georgia with an electric load of 9,600 watt-hrs./day using thin-film PV cells with a mid-range efficiency of 13 watts/SF to generate 50% of the electric load, the results could be as follows:

with a 'Composite' climate tilt angle of PV array = latitude (i.e., 34°)
winter sun-hours = 3 hours
summer sun-hours = 5 hours

Since the winter PV array area (123 SF) is larger than the summer PV array area (73 SF) but not excessively large it will become the selected area:

selected PV array area = **123 SF**
typical amount of electricity generated in winter = (123 x 13 x 3) = 4797 watts/day
typical amount of electricity generated in summer = (123 x 13 x 5) = 7995 watts/day
annual electric load = (365 x 9600 / 1000) = **3,504 kilowatts**
annual solar PV electricity generated = 2,434 kilowatts
surplus electricity generated = **0 kilowatts**
deficit electricity drawn from the grid = (3504 - 2434) = **1,072 kilowatts**

5.11 Questions Relating to Chapter 5

Answers to the following multiple-choice questions with references to the appropriate text (by page number) may be found at the back of the book.

1. **The amount of solar heat energy incident on the earth's <u>atmosphere</u> is approximately:**

   A. 1000 BTU/SF-HR
   B. 440 BTU/SF-HR
   C. 4000 BTU/SF-HR
   D. 40 BTU/SF-HR
   E. None of the above is correct.

2. **It is unlikely that more than X% of the total national energy consumption in the United States can be satisfied with solar energy by the year 2020. What is the missing percentage (i.e., X%)?**

   A. 10%
   B. 20%
   C. 30%

D. 40%
E. 50%

3. **The amount of solar heat energy incident on the earth's <u>surface</u> is in the approximate range of:**
   A. 10 to 100 BTU/SF-HR
   B. 100 to 300 BTU/SF-HR
   C. 300 to 600 BTU/SF-HR
   D. 600 to 900 BTU/SF-HR
   E. None of the above is correct.

4. **Which of the following United States cities is most likely to experience a mean daily solar radiation of 3,000 BTU/SF on a sunny winter day?**
   A. Los Angeles
   B. Las Vegas
   C. Indianapolis
   D. Boston
   E. None of the above is correct.

5. **The low quality nature of solar energy is not a deterrent for water and space heating applications, where temperatures seldom exceed:**
   A. 68˚F
   B. 150˚F
   C. 73˚F
   D. 212˚F
   E. None of the above is correct.

6. **The principal difference between ACTIVE and PASSIVE solar systems is that:**
   A. ACTIVE systems are more reliable.
   B. ACTIVE systems utilize mechanical components and PASSIVE systems do not.
   C. PASSIVE systems require an auxiliary back-up system and ACTIVE systems do not.
   D. All of the above are correct.
   E. None of the above (i.e., A, B and C) is correct.

7. **The efficiency range of an unglazed flat plate solar collector is approximately:**
   A. 20% to 30%
   B. 55% to 65%
   C. 60% to 80%
   D. Insufficient information.

E. None of the above is correct.

8. **The efficiency range of a double-glazed flat plate solar collector is approximately:**

   A. 20% to 30%
   B. 55% to 65%
   C. 60% to 80%
   D. Insufficient information.
   E. None of the above is correct.

9. **To prevent a liquid flat plate solar collector from freezing in winter in cold climates you would:**

   A. Use salt water as the heat transfer medium.
   B. Cover the collector with opaque 20 mil. PVC film.
   C. Artificially heat the liquid in the collector.
   D. Remove the collector and store it in a warm place.
   E. None of the above is correct.

10. **If the density of water is approximately 62 LB/CF then the heat capacity (in BTU/CF -°F) of water is about:**

    A. 31
    B. 62
    C. 93
    D. 124
    E. None of the above is correct.

11. **As a rule of thumb __"X"__ gallons of water (heat storage) are normally required per square foot of flat plate solar collector. "X" is equal to:**

    A. 1 to 10
    B. 10 to 20
    C. 20 to 30
    D. 30 to 40
    E. None of the above is correct.

12. **Rock heat storage units normally require about _____________the volume of an equivalent water heat storage tank. Fill in the missing words:**

    A. 5 times
    B. 1.5 times
    C. 2.5 times
    D. 3.5 times
    E. None of the above is correct.

13. **In a rock heat storage unit, the sizes of typical pebbles normally range from about:**

    A. 1 IN to 3 IN
    B. 3 IN to 6 IN
    C. 6 IN to 12 IN
    D. Insufficient information.
    E. None of the above is correct.

14. **One advantage of a rock heat storage unit over a water tank is that:**

    A. Rocks are cheaper than water.
    B. The rock storage unit is <u>not</u> subject to heat stratification.
    C. Rock storage units are smaller.
    D. All of the above are advantages of rock heat storage units
    E. None of the above is correct.

15. **As a rule of thumb, under favorable weather conditions, we would expect no more than "X" SF of a single glazed flat plate solar collector to be required to heat forty (40) gallons of water from a main's temperature of 60°F to 120°F. "X" is approximately:**

    A. 100
    B. 80
    C. 60
    D. 40
    E. 20

16. **For winter heating, the optimum tilt angle of a solar collector is approximately:**

    A. Longitude + 15°
    B. 45°
    C. Latitude + 1°
    D. 90°
    E. None of the above is correct.

17. **For combined winter heating and summer cooling, the optimum tilt angle of a solar collector is approximately:**

    A. Longitude + 15°
    B. 30°
    C. Latitude + 5°
    D. 60°
    E. None of the above is correct.

18. **If during January the average external temperature is -10° F for a certain location, and each day of that month has "X" DEGREE DAYS, "X" is approximately:**

    A. 45
    B. 55
    C. 65
    D. 75
    E. None of the above is correct.

19. **If the heat loss of a building is 50,000 BTU/HR and the building is located in a 500 degree day zone for January, then the heat loss per degree day for this building in January will be:**

    A. 100 BTU/DD
    B. 3,100 BTU/DD
    C. 2,400 BTU/DD
    D. Insufficient information
    E. None of the above is correct.

20. **According to the Skytherm roof pond concept of passive solar architecture:**

    A Insulation panels are used to shade the building interior from the sun.
    B. An adjacent greenhouse is used as a heat store.
    C. Skylights are used in the roof to allow the sun to heat the building interior.
    D. The thermo-siphoning effect is used to circulate water from solar collectors to water bags at roof level.
    E. None of the above is correct.