SOLAR ENERGY TECHNOLOGY HANDBOOK

Part B

Applications, Systems Design, and Economics

Editors

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PREFACE

Solar energy, as generally defined, includes energy derived directly from sunlight as well as indirectly in the form of wind, waves, tides, ocean thermal gradients, or as fuel from biomass and other photochemical reaction products. Over the past several years there has been an explosive growth in solar energy research, development, and demonstration, particularly in the United States.

In 1972 a solar energy panel, organized by the National Science Foundation and the National Aeronautics and Space Administration, made the first comprehensive assessment of the potential of solar energy as a national energy resource.* They also examined the state of the technology in the various solar energy application areas. The total U.S. budget for solar R&D in that year was $1.7 million. In 1979 the annual U.S. solar budget had increased to $550 million and is expected to be more than $700 million in 1980.

This tremendous increase in government funding, not only in this country but in several other countries, has resulted in a proliferation of new ideas and concepts as well as a large increase in available information and data in all of the solar technologies. Hence there is a need for a comprehensive handbook describing the present state of knowledge and offering the best available information and data in each solar energy technology. It is hoped that this *Solar Energy Technology Handbook* will fulfill this requirement.

Although there may, indeed, be "nothing new under the sun," it is highly probable that in the coming years there will be technical and economic "breakthroughs" in almost all of the solar technologies covered in this handbook. New materials and new measurement techniques will be developed. There will be a continued advancement and refinement of theoretical understanding. Although a serious effort has been made by each of our contributing specialists to present the fundamentals of theory and experiment that will have enduring value, this handbook can represent only the present state of knowledge. The handbook is intended to supply the practicing engineer/scientist and student with an authoritative reference work that covers the field of solar engineering as well as peripherally related fields. References and primary citations are given to the extensive solar literature for those who wish to dig deeper.

**Solar Energy as a National Energy Resource*, Prepared by the NSF/NASA Solar Energy Panel, December 1972. Co-chairmen: Dr. Paul Donovan and Mr. William Woodward; Executive Secretary: Mr. William R. Cherry; Technical Coordinator: Dr. Frederick H. Morse; Executive Committee: Dr. Lloyd O. Herwig.

The handbook, for convenient use, is divided into eight main units: (1) The Solar Resource; (2) Solar Thermal Collectors; (3) Photovoltaics; (4) Bioconversion; (5) Wind Energy; (6) Solar Energy Storage Systems; (7) Applications of Solar Energy; (8) Non-technical Issues. In addition there are three Appendixes containing unit-conversion tables and useful solar data. It became obvious early in this project that if proper coverage were to be given each of these areas it would be necessary to divide the handbook into two volumes. The first six units constitute Part A, Engineering Fundamentals and the last two units constitute Part B, Applications, Systems Design, and Economics. These volumes have been prepared primarily as reference books, but it is felt that many of the sections will prove useful for practicing engineers, scientists, and students.

The subject of units has been a troublesome one in assembling this handbook. We were tempted to take a purist approach and insist on the strict and exclusive usage of SI units throughout. However, this did not seem practical or desirable. Since solar energy is an applied engineering technology, the use of English units (feet, horsepower, Btu, psig) is still deeply entrenched in the United States. However, the change to metric units (meters, kilowatts, joules, pascals) is well underway in all technical areas. We have attempted to soften the transition by asking our contributors to give the equivalent value in English units parenthetically after the metric value, except for the simpler units where metric is used alone. We do not claim 100 percent success in this effort, particularly in some of the tables and graphs. To make life easier for confirmed users of either set of units, a comprehensive set of conversion tables is included as Appendix A at the back of each volume.

To ensure the highest degree of reliability the cooperation of a large number of specialists has been necessary, and this handbook presents their efforts. Our heartfelt thanks go to the 58 contributors, each of whom has endeavored to present an authoritative and up-to-date overview of his/her area of solar expertise and has given willingly of very valuable time and knowledge. The editors also wish to thank Marcel and Mau Dekker, the publishers, and Graham Garratt, for their encouragement and constructive suggestions.

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APPLICATIONS OF SOLAR ENERGY

chapter 27

DOMESTIC WATER HEATING

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27.1 HISTORICAL BACKGROUND AND CURRENT PERSPECTIVE

Solar domestic hot water (DHW) heaters have had a long and varied history. In the United States, solar water heaters were first used in the warm and sunny climates of southern California and Florida. Interesting tales of the early commercialization of solar energy are portrayed by Butti and Perlin [1] and Scott [2]. The following two paragraphs are adapted from these two references, respectively.

In southern California, the solar water heater industry started in about 1891, flourished during 1909-1920, and died around 1930. The early solar water heaters were of the combined collector-storage type, in which shallow, blackened metal water tanks are enclosed in pine boxes, covered with glass, and exposed to the sun. Hot water from these units had to be used up during the day, otherwise the heat would be lost during the night. In 1909, W. J. Bailey invented the Day and Night Solar Water Heater, which separated the collector from the storage tank and which was very similar to the present-day Thermosiphon solar water heater. These units sold well. By the end of World War I about 4000 units had been sold, and sales peaked in 1920 with more than 1000 units sold. The units sold for about \$100 installed for a 40-ft^2 collector and a 40-gal storage tank (1910-1920 dollars). The units sold for purely economic reasons, as the backup natural gas cost about \$3.20/MCF in 1900.* Solar water heater sales decreased in the late 1920s with the advent of automatic storage-type natural gas water heaters and cheap natural gas. This history is told in an interesting illustrated article by Butti and Perlin [1].

In southern Florida, the early solar water heater industry flourished during the 1940s and 1950s in the Miami area. It is estimated that as many as 60,000 solar water heaters may have been installed during this period. These solar water heaters were of the thermosiphon type shown in Fig. 27.1. During the peak sales period of the late 1940s, an 82-gal unit with a 48-ft^2 collector cost about \$350 installed, and the backup electricity price was about 4¢/kWh [2]. The demise of the early solar water heater industry in Florida can be attributed to the rising installed cost of solar water heaters, the declining cost of electricity, and the convenience of automatic electric water heaters.

In today's age of renewed interest in solar energy, solar domestic hot water heaters are again prominent in the sales of solar systems. This is to be expected, since solar domestic water heaters, when compared to solar space heating and cooling systems, (a) have maximum utilization due to the near-constant hot water load in residences throughout the year, (b) are the simplest mechanically, (c) are the lowest in first cost, (d) are retrofittable to existing houses and, (c) are most economical because of the above reasons. Present-day solar water heaters cost between \$1000 and \$3000 (1980 dollars) installed depending on the collector size (4 to 8 m^2) and the system type. Direct water heaters with minimal freeze-protection devices suitable for mild climates cost between \$1000 and \$2000 and closed-loop antifreeze systems with heat exchangers cost between \$2000 and \$3000. There is a wide variety of system types and configurations marketed by a large (more than 100) number of companies today. The market potential is excellent, because domestic hot water accounts for about 15 percent of U.S. residential energy use. A recent survey [3] shows that more than 2000 solar water heaters were installed in Florida residences alone in the first 6 months of 1977. Fifty-nine percent of the installations were retrofit and 41 percent new. Average installed cost was \$375/m^2 for residential and \$300/m^2 for commercial installations. Solar water heaters are popular worldwide today, particularly in Israel, Australia, Japan, and South Africa.

27.2 DESCRIPTION OF SOLAR DHW HEATERS

As of 1978, a wide variety of solar DHW systems are being sold. The proliferation of system types is due to the necessity of tailoring system configurations to climatic regions as well as to the fact that the reborn solar industry is still not mature. In the material that follows, the more common types of solar DHW systems are described and their operating principles examined. Freeze proofing solar systems is very important, as a single freeze may destroy the costly collectors. Indeed, the variety of system configurations is due mainly to the different ways the systems are protected against freezing. Two excellent references, one by McCabe et al. [4] and by ITT design manual [5], should be consulted for details of system hardware integration and various other topics.

The primitive combined collector-storage type of solar water heater is rarely used today and will not be discussed further. The systems used today have the collectors and

*1 MCF = 1000 ft^3 ≅ 1 MBtu.

storage tanks as separate units interconnected by plumbing. More than 90 percent of the solar DHW heaters currently being installed in the United States are of the "pumped" variety, in which the collector fluid is circulated by a small electric circulating pump operated by a controller and the storage tank is installed within the house to protect it from freezing. A wide variety of pumped systems are described later. The other type of solar water heater is the thermosiphon water heater, which does not use a pump or a controller.

The following system types will be described:

Thermosiphon system (Fig. 27.1)
Pumped direct system with freeze protection by hot tank water recirculation (Figs. 27.2 and 27.3)
Pumped direct system with automatic draindown (Fig. 27.4)
Pumped indirect system with automatic draindown (Fig. 27.5)
Pumped indirect system with antifreeze (Figs. 27.6 and 27.7)
Pumped indirect system with air collectors (Fig. 27.8)

A. Thermosiphon System

Figure 27.1 shows a typical thermosiphon solar water heater. The entire system is under city water pressure, and no pumps or controllers are required for system operation. The solar preheat tank is located above the collectors. In the morning as the sun heats the collectors, the hot water inside rises by natural convection and the colder storage-tank water flows into the collectors by gravity. Thus the circulation loop is automatically established whenever there is sufficient sunshine, and circulation automatically stops during insufficient insolation when the upward buoyancy force is unable to overcome the fluid friction losses inside the plumbing. In order to prevent reverse circulation at night, the tank should be located above the collectors. During bright sunshine, collection flow rates between 40 and 60 $l/h \cdot m^2$ (1 and 1.5 $g/h \cdot ft^2$) of collector can be achieved in a well-designed system. The plumbing must continuously slope upward with smooth bends to prevent air pockets which, if formed, can cause flow stoppage. To minimize fluid friction losses, the collector piping must be at least 1.9 cm (3/4 in.) I.D.

As shown, the cold water enters the bottom of the preheat tank and the collector return is located at the top of the tank to promote stratification and collection efficiency. An auxiliary heater provides hot water during inclement weather. A mixing valve (M), as shown, keeps the household hot water supply at the desired temperature by mixing cold water with the auxiliary tank water if it is too hot. The check valve (C) on the cold water inlet is necessary to satisfy building codes and prevents backflow to the city mains if the system fails. The contents of this paragraph on stratification, mixing valve, and backflow preventer are applicable to all the system configurations to be described later, as can be seen in Figs. 27.2 through 27.8.

It is inconvenient to freezeproof thermosiphon systems. The system shown can be drained manually only by closing the collector isolation valves V and opening the draincocks D. It is also possible to employ a heat exchanger inside the preheat tank and to use antifreeze in the collectors to permanently freezeproof the system.

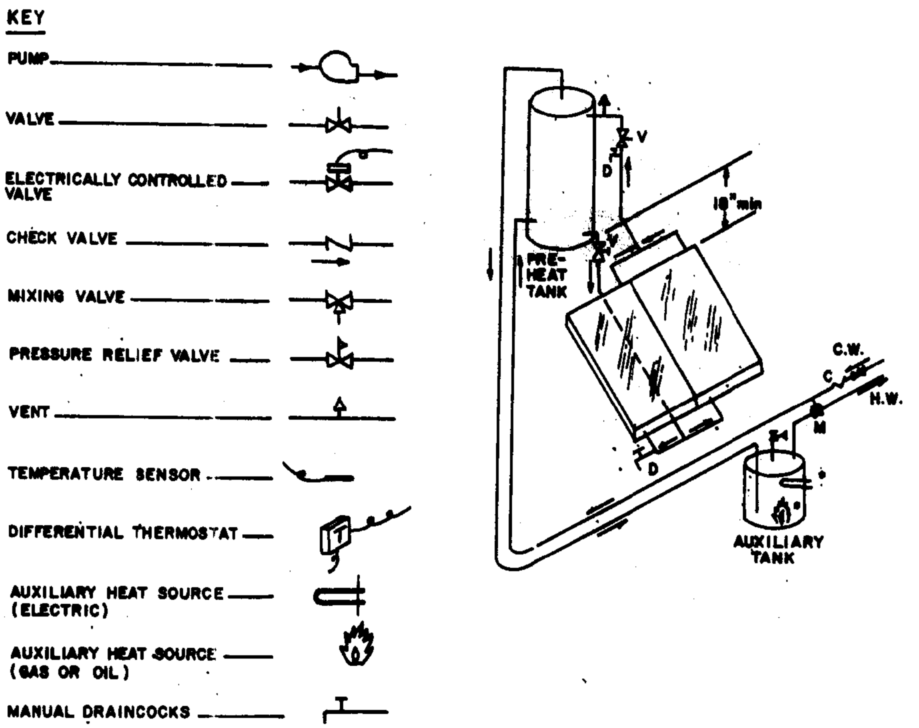

Figure 27.1 A thermosiphon solar water heater. * Denotes that either auxiliary energy source is acceptable. (From NBSIR 77-1272.)

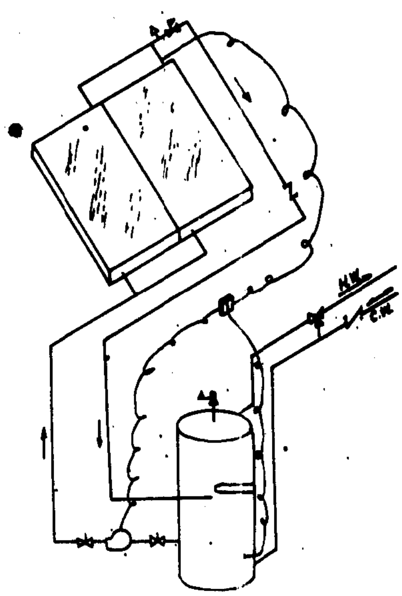

Figure 27.2 Direct heating with a single tank. (From NBSIR 77-1272, July 1977.)

There are advantages and disadvantages to thermosiphon systems. The greatest advantage is that the system is totally automatic requiring no electricity to run pumps or controls. This had led to the widespread use of thermosiphon systems in the early days of U.S. solar industry, and even today many solar water heaters in other countries are of this type. The disadvantages are also noteworthy. First, the installation is difficult and costly, since the heavy preheat tank must be located above the collectors. Since collectors are usually mounted on the roof, this necessitates that the storage tank be placed inside the attic or mounted on the roof with a false chimney jacket to improve its appearance. The water tank can damage the roof of the house interior if it leaks. Second, it is difficult to freezeproof and retrofit. For these reasons not many thermosiphon water heaters are installed today in the United States, although they perform as well as or better than pumped systems.

B. Pumped Systems

The remainder of this subsection discusses pumped solar DHW systems. Some general remarks on pumped systems are made before proceeding to individual system descriptions.

All pumped systems have at least four basic solar components, the collector(s), the storage tank(s), the control system, and the circulation pump(s). See Fig. 27.2 for an example. In pumped systems the absorbed energy in the collector is transferred to the storage tank by forced circulation of the collector fluid by a pump. The pump is controlled (turned on and off) by an electronic differential controller. The controller has two sensors, one mounted at the collector outlet and the other near the bottom of the tank. In the morning, as the sun heats up the stagnant collector fluid to a temperature about 6 to 10°C above the storage tank bottom temperature, the controller turns the pump on. This 6 to 10°C differential temperature needed to activate the pump is called the turn-on ΔT. As the circulation is established, ΔT between collector and storage drops to about 3 to 5°C. If the sunshine is insufficient to maintain a ΔT of 0.5 to 1.5°C (the turn-off ΔT), the controller stops the pump. The turn-on and turn-off ΔT's can be adjusted on some controllers. So far the above discussion assumes fixed flow-rate pumps, which are the most widely used pumps for solar DHW systems. Recently some have started using proportional flow controls which vary the pump speed to collect a greater amount of energy. See Ref. 6 for a discussion of proportional flow controllers.

Another control scheme uses thermostatic snap switches. The pump is turned on whenever the collector switch senses a temperature of 55 to 60°C and turned off when the temperature drops below 45°C. To prevent hot tank water from circulating through the collector, another snap switch mounted near the tank bottom prevents circulation if the tank bottom temperature is greater than 45°C. Although less efficient, snap switch controllers may be more reliable.

In order to maximize collector efficiency, one needs to supply the collectors with the lowest possible fluid temperature. This is the reason for taking the collector supply from the bottom of the tank in a direct water system as shown in Fig. 27.2. In order to promote stratification, the collector return is connected to the top of the solar storage tank if it does not contain an electric backup element. If it does, as in Fig. 27.2, the collector return should be connected below the element. This small detail can improve system performance by up to 40% by preventing backup electric use during mornings.

It is also a good idea to have the backup element operated by a timer so that it never comes on during the day. This will be even more important when time-of-day pricing is introduced by the utilities.

The various pumped systems will now be discussed. The basic energy-collection mechanism is similar to all as discussed above. The differences arise in the various ways the collected heat is transferred to the hot water tap and in the different freeze-protection methods. There are two principal types, the direct heating systems (Figs. 27.2 through 27.4), in which the tap water is circulated through the collectors via a storage tank, and the indirect heating systems, in which a different fluid is employed in the collectors (Figs. 27.5 through 27.8). Direct systems are more efficient and more suitable for milder climates with, say, less than 45 freezing nights per year. Indirect systems, although about 10 to 15 percent less efficient, are better protected against freezing and thus more suitable for colder climates.

C. Direct Solar Water Heaters

Figure 27.2 shows the simplest direct solar water heater with a single tank. The entire system is under city pressure. The single tank serves as both the solar storage and auxiliary tank. This type of a system must have an electric backup. Fossil fuel backup will keep the entire tank water at least at the water set-point temperature. This will greatly reduce collector efficiency. The electric elements heat water above the element and therefore the water at the tank bottom gets a chance to cool off. Freeze protection in this system is achieved by automatic recirculation of hot tank water during cold nights. As the ambient night temperature drops below about 1.5°C (35°F), a separate freezestat sensor in the collector (or in some designs the same collector sensor can serve a dual

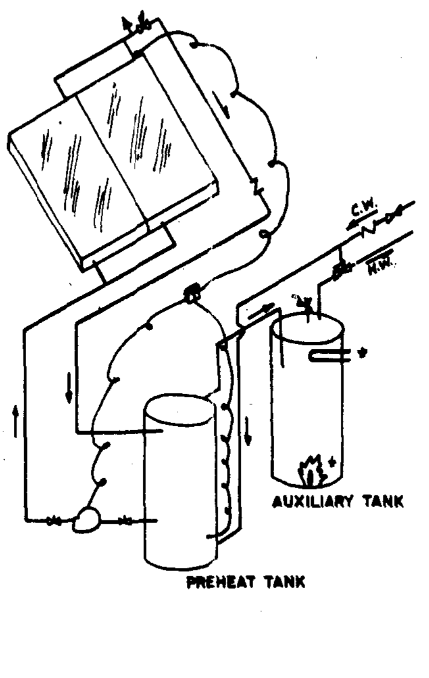

Figure 27.3 Direct heating with preheat tank and separate auxiliary tank. * Denotes that either auxiliary energy source is acceptable. (From NBSIR 77-1272.)

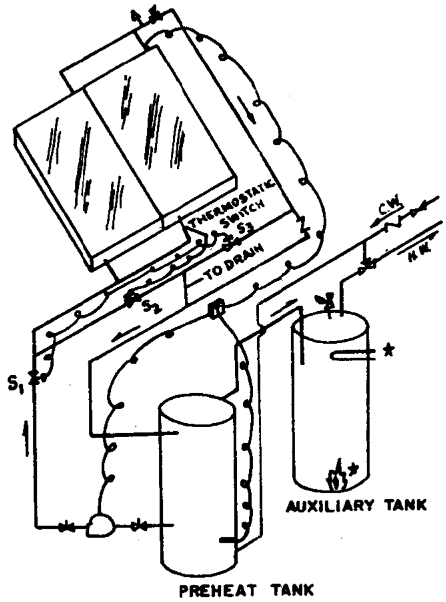

Figure 27.4 Direct heating with preheat tank and automatic draindown. * Denotes that either auxiliary energy source is acceptable. (From NBSIR 77-1272.)

purpose with another lead) turns on the pump. A check valve located in the collector return line prevents thermosiphon of the hot tank water through the cold collectors at night. Check valves in solar systems are known to fail frequently. Therefore many systems today use a solenoid-operated ball valve which opens only when the pump is on.

Figure 27.3 shows a two-tank design based on the same principles. Note that the solar preheat tank does not contain any auxiliary, and this increases solar collection efficiency. The auxiliary tank can be the existing house hot water tank for retrofit situations. The preheat tank should be sized for the entire solar system. In other words, the auxiliary tank storage volume should not be counted as partly meeting the storage size requirements. This is because the auxiliary tank does not normally store any solar heat. The solar-heated water goes to the auxiliary tank only when there is a draw from the house hot water faucets. As before, hot water is recirculated on cold nights for freeze protection. Two-tank systems are a necessity if conventional oil or gas water heaters are to be used as a backup. For systems with electrical backup a one-tank system is preferable due to its superior performance and reduced cost. The substantial tank heat losses from two-tank systems decrease their performance when compared with one-tank systems.

Figure 27.4 shows an automatic draindown system very similar to that sketched in Fig. 27.3 except that the collectors are automatically drained during cold nights by thermostatically controlled electric solenoid valves. During cold nights or during power failure, solenoid valve S_1 shuts off, and S_2 and S_3 open to drain the collectors. In solenoid valve terminology, S_1 is a "normally closed" and S_2, S_3 are "normally open" valves. The word "normal" in solenoid valve terminology refers to the unenergized state of the valve (e.g. when it is in a packing box). Further information on direct systems, including installation procedures, may be found in Ref. 7.