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SCIENCE

Solar Heating and Cooling

Solar energy for buildings is developing rapidly in the United States.

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Thermal energy for buildings, supplied at temperatures near or below 100°C, constitutes an important segment of the U.S. energy economy and accounts for about one-quarter of the nation's energy use. Energy at these temperatures can readily be delivered from flat-plate solar energy collectors, and the solar energy incident on most buildings is more than adequate to meet these energy needs. Flat-plate collectors are manufactured and sold on a small but growing scale in the United States; they have been in use for more than a decade in heating water for buildings in Australia, Israel, and Japan. We expect that solar heating and cooling for buildings, with energy collected by flat-plate collectors, will be the first large-scale application of solar energy.

The basic problem with solar heating and cooling has been that the energy could not, except in special cases, be delivered at costs competitive with costs of energy from other sources. This situation is rapidly changing, and interest in solar energy is increasing almost daily as fuel costs rise. In areas where new natural gas connections are no longer available, where oil is not distributed, and where electrical resistance heating is the only alternative among conventional sources, solar heating is economically attractive.

In addition to technical and economic considerations, several social factors will influence the course and pace of developments. Two examples are worth examining. First, architectural constraints are imposed by the need for collectors to be oriented within rather narrow limits. This will make it difficult to fit solar heating systems to many existing buildings; thus new residential construction will be the easiest starting place for conversion to solar heating. Solar cooling may first be installed in existing low-rise, flat-roof buildings such as schools and shopping centers, where cooling is usually more important than heating. Second, tax policy is important. Today the installation of solar heating or cooling systems brings an increase in property valuation in most states, and a corresponding modest increase in real estate taxes. Government encouragement to invest in solar energy systems in the form of tax write-offs or other inducements (as are provided for investments by other energy producers) could very rapidly change the competitive position of solar energy in relation to conventional energy sources.

In all buildings, intelligent practices for energy conservation are worth following. The basic advantages of reducing energy needs by good thermal design apply whether buildings are supplied with solar or conventional energy. If solar energy costs the same as an alternative energy source, the value of energy conservation techniques, such as extra glazing on windows and doors or added insulation, is the same whether solar energy or the alternative is being used.

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Solar Radiation

The solar constant, that is, the intensity of solar radiation outside of the earth's atmosphere at the mean distance between the earth and the sun, has been determined by measurements from satellites and high altitude aircraft to be 1.353 kilowatts per square meter (*1*). This extraterrestrial radiation, which corresponds closely to that of a blackbody at 5762°K, is 7 percent in the ultraviolet range (wavelength less than 0.38 μm) and 47 percent in the visible range (wavelengths from 0.38 to 0.78 μm), with the balance in the near infrared (largely with wavelengths of less than 3 μm).

Solar radiation is depleted as it passes through the atmosphere by a combination of scattering and absorption; the radiation that reaches the ground—the raw material of this energy source—can vary from almost none under heavy cloud cover to 85 to 90 percent of the solar constant under very clear skies. Energy rates on surfaces normal to the radiation during good weather are not very high, and are typically about 1 kilowatt per square meter (a little more than 1 horsepower per square yard). Solar radiation on the ground consists of a diffuse component that has been scattered by molecules and particulate matter in the atmosphere and, when the atmosphere is sufficiently clear, a beam component that is unchanged in its direction of propagation from the sun. Its spectral distribution is altered in a manner dependent on atmospheric composition, with the major changes due to absorption of ultraviolet radiation by ozone and infrared radiation by water vapor.

There are several sources of solar radiation data. The National Oceanic and Atmospheric Administration weather service measures total (beam diffuse) radiation on a horizontal plane at more than 100 stations. Some stations report daily values, and some report hourly values. These data are available from the National Climatic Data Center (*2*). Monthly averages of daily radiation on horizontal surfaces are available for many locations (*3*). Daily integrated energy quantities at particular locations vary widely during the year. In Madison, Wisconsin, on a clear

January day, energy on a horizontal surface is typically 3 kilowatt-hours per square meter, and July clear-day energy is typically 9 kw-h/m^2; the corresponding monthly averages of daily radiation on the horizontal surface are 1.8 kw-h/m^2 and 6.2 kw-h/m^2. Flat-plate collectors sloped toward the south in Madison, with a slope equal to the latitude, will have incident on them an average daily radiation of 3.4 kw-h/m^2 in January and 5.6 kw-h/m^2 in July. These data illustrate the gains to be obtained by orienting a collector in a favorable manner.

Although solar energy intensity is low, integrated energy quantities may be large. For example, in Madison the annual average solar energy incident per day on an acre of ground is the equivalent of about 10 barrels of oil, and on a 200-m^2 house is equivalent to about 25 gallons, which is far more than enough to meet the needs of the building for thermal energy.

Current Status

Two major reasons may be cited for the failure of solar energy to be a serious competitor in the energy market in past years. First, the costs of delivering solar energy have been substantially higher than those of other energy sources. Solar energy has not been able to be a competitor to inexpensive natural gas or petroleum. Second, there was no constituency pressuring for solar energy development in a manner similar, for example, to that of the nuclear industry that existed at the close of World War II and gave a substantial impetus to the development of peacetime uses of nuclear energy. The environmental movement of the last 5 years, the realization that the United States is dependent to an undesirable degree on foreign energy sources, and increasing fuel costs have served to establish a broad base of interest in developing solar energy.

The contrasts between the development of nuclear energy and solar energy are striking. After the destruction wrought by the atomic bombs in World War II, a large, concerned constituency, backed by the nation at large, pushed for devel-

Fig. 1. Solar building architecture. (a) Löf home in Denver, Colorado. (b) Retrofitted collectors on school in Boston [photo courtesy of General Electric]. (c) Collector built into south wall of house of Odeillo, France. (d) MIT house IV, Massachusetts. (e) CSU house I, Fort Collins, Colorado. (f) Retrofitted house in Denver, designed by R. L. Crowther.

opment of peaceful uses of atomic energy. The result was a program supported by billions of dollars of federal funds over the course of three decades. Solar energy, in contrast, had no such support and it was only the persistence of a few individuals that kept interest in solar energy alive. Outstanding in this group was Farrington Daniels, who, through his publications (*4*) as well as through his support of the struggling International Solar Energy Society, served as an elder statesman for solar energy.

During the 1960's support for solar energy research for applications in the United States was essentially nonexistent. However, one program resulted in economic studies that have become part of the current interest in solar energy. Tybout and Löf, with support from Resources for the Future, developed a series of cost analyses of solar energy for heating and cooling (*5*). They indicated that solar heating could be competitive with conventional energy sources in high energy cost areas in 1968. They also showed that the combination of solar heating and cooling, which results in higher use factors on the solar energy equipment, is, in most places, more economical than heating or cooling alone. Their two studies were based on optimistic projections of the cost of solar energy equipment ($20 and $40 per square meter of flat-plate collector), but also on 1968 and 1970 energy costs. Later and more detailed studies of cost and thermal performance, based on more realistic collector and energy costs, bear out the same general conclusion that solar heating can now compete with expensive fuels.

By 1972, several dozen solar-heated residences or small laboratory buildings had been constructed and operated. A few of these have been studied, evaluated, and reported (*6*). The few air conditioning experiments were confined largely to experimental operation of 3-ton LiBr-H_2O absorption machines or analytical studies of system performance (*7*). In contrast, the manufacture and sale of solar water heaters to provide hot water for residences and some institutional buildings (hotels, dormitories, and the like) has been a commercial enterprise in Australia, Japan, and Israel for more than a decade. Perhaps a million solar water heaters are in use in these countries.

During the past 3 years, the availability of funds for experimental programs from the NSF Research Applied to National Needs (RANN) program and the Energy Research and Development Administration (ERDA), coupled with private and industrial investment, has led to many new experiments and applications of solar heating and cooling in the United States. Public buildings, schools, and a variety of residential buildings with heating or combined heating and air conditioning capacity are being planned and built. Quantitative information is now beginning to come in from these new experiments (*8*). The Solar Heating and Cooling Demonstration Act of 1974 should lead to many new solar buildings. In addition to research and development activities, there are now a few sales of solar heating systems which are installed as operating heat delivery systems rather than as experiments.

Solar Building Architecture

Several approaches to solar building architecture are evident. Several solar-heated houses and a school are illustrated in Fig. 1. The basic problem faced by architects and engineers is to integrate collectors into or onto the building in such a way that thermal performance is adequate, while obtaining an esthetically satisfactory structure. In this context, the major variable is the area of collector that must be integrated into the building. Collector area is central to the fraction of heating loads to be carried by solar energy and, ultimately, to cost.

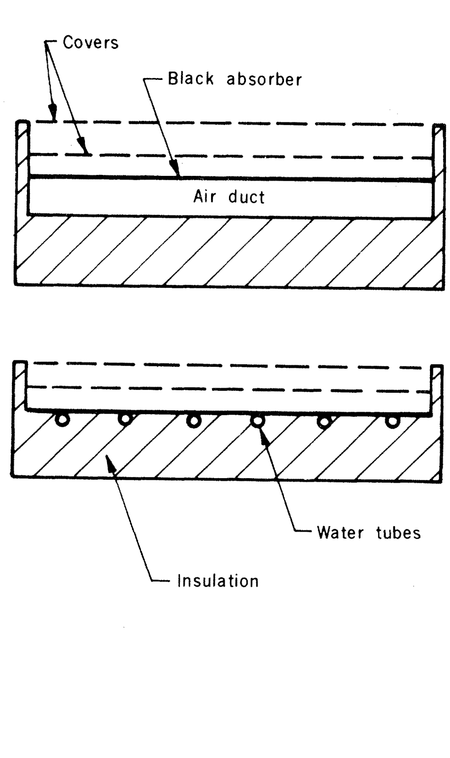
The solutions are mixed. Some collectors have been mounted above flat-roof buildings (Fig. 1, a and b). To obtain structural or esthetic advantages, other collectors have been built into vertical walls in higher latitudes (Fig. 1c) or placed flat on horizontal roofs in lower latitudes. In addition, collectors have been integrated into the envelopes of buildings at orientations that are near optimum for the best thermal performance (Fig. 1, d to f).

Solar Energy Systems

Systems for producing service hot water, space heating, and cooling are based on the concept of the flat-plate collector. This unique heat exchanger uses a black absorber plate to absorb solar energy. Ducts or tubes carry air or liquid that remove energy from the plate. Layers of air provide transparent insulation between plates and their covers (usually made of glass) and thus reduce upward heat loss. Conventional insulation is provided on the backs and edges of the plates. The collectors are mounted in a fixed position according to the desired use of the energy. Figure 2 shows cross sections of air and water heaters.

The other major component in the system is the energy storage unit which is designed to accumulate solar energy when it is obtainable and make it available to meet energy needs at other times. Liquid systems usually use insulated water tanks for storage, and air systems usually use pebble beds. A third method of storage takes advantage of the latent heat of a phase transition, and has been the object of considerable study (*9*). Early work on house-heating applications concentrated on $Na_2SO_4 \cdot 10H_2O$, which undergoes a phase transition when heated at 32°C. Because phase separation of this hydrate occurs on cycling, other chemical systems are being sought which can undergo thousands of cycles without loss of storage capacity.

Schematic diagrams of liquid and air solar heating systems are shown in Fig. 3. Both show an auxiliary energy source, which is included in most solar energy systems. In climates where a high degree of reliability is required of a heating system, the auxiliary source must be capable of



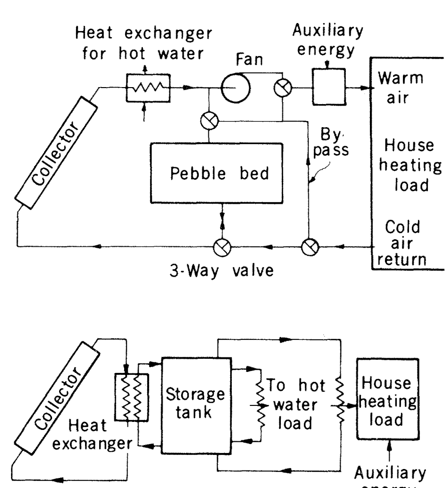


Fig. 2 (left). Cross sections of a solar air heater and a solar water heater. Fig. 3 (right). Schematic diagrams of solar heating systems based on air and liquid heat transfer media.

carrying the full heating load of the building. If auxiliary energy is added in parallel with solar energy, then the maximum amount of energy can be obtained from the solar system and the balance from auxiliary. Other methods are possible.

For the liquid system the heat exchanger between collector and storage tank allows the use of an antifreeze solution in the collector loop, which is one of the methods to avoid freezing and reduce boiling problems. The diagram shows an additional heat exchanger to transfer heat to the building, and another to provide service hot water. The technology of solar liquid heaters is very well established, and most of the systems built recently have used liquids for heat transfer.

Air systems avoid boiling and freezing problems in the collector. In most air systems energy is stored as sensible heat in a pebble bed. A well-designed pebble bed has good heat transfer between air and pebbles, a low loss rate, and a high degree of stratification. Mechanical energy for pumping air can be a significant item of cost, and care is required to design for minimum pressure drops. The design of air systems and the balancing of good heat transfer characteristics against pressure drop are problems that are now receiving adequate attention.

Table 1. Performance data for MIT house IV for two heating seasons [summarized from Engebretson (*6*)]. Numbers are expressed in gigajoules.

Item	1959 to 1960	1960 to 1961
Space heating		
Demand	72.5	70.7
From solar energy	33.6	40.2
Water heating		
Demand	14.7	17.6
From solar energy	8.4	9.7
Total heating		
Demand	87.1	88.3
From solar energy	41.9	49.9
Percent from solar energy	48.1	56.6

Many of the scores of solar-heated buildings that have been constructed so far have provided reduced fuel bills as well as satisfaction to their owners. The performance of a few of these has been carefully measured, and provides a firm base of data on long-term thermal performance. Experiments up to 1961 were very well reported in papers presented at the U.N. Conference on New Sources of Energy in 1961 and summarized by Löf (*6*).

Massachusetts Institute of Technology (MIT) house IV, built in 1959, was the last in a series of experiments carried out by H. C. Hottel and his colleagues and represented a cooperative effort of architects and engineers to develop a functional, energy-conserving home with a major part of the energy for space heating and water heating to be supplied from the flat-plate collector. Figure 4, from Engebretson (*6*), is a schematic diagram of the heating and hot water system. The collector had an area of 60 m^2 for the 135-m^2 floor area, two glass covers, and a flat, black paint, energy-absorbing surface. To avoid freezing, collectors were designed to drain into an expansion tank. The main storage tank capacity was 5700 kilograms. Means were provided for adding auxiliary energy, extracting hot water for household needs, and transferring heat to air that was circulated to the rooms. This solar heating system was operated for three seasons, during which its performance was carefully measured. Data for the first 2 years are summarized in Table 1, which shows how energy requirements for space heating and water heating were met by solar or auxiliary energy. During the first two heating seasons solar energy supplied 52 percent of the energy for hot water and heating.

The Denver solar house, built by Löf (*6*) in 1958, uses air as the heat transfer medium and a pebble bed storage unit. The ratio of collector area to house area is about 1 to 5, a proportion much smaller than that of MIT house IV. This house has served as the Löf family residence since its construction, and the equipment has been routinely operated with only nominal maintenance. The system performance was measured in 1959 to 1960, and again in 1974 to 1975. For the period from December to April, 22 percent of the heating and hot water loads were carried by solar energy during the earlier season, and 20 percent during the later season.

Solar air conditioning technology is not as advanced as the heating process, since an additional thermodynamic process is needed for cooling. Several current experiments use absorption cooling cycles that are operated by heat from flat-plate collectors. These coolers are the analogs of the gas-fired refrigerators used in campers, but due to the lower temperature of fluid from the collectors (compared to a gas flame), water cooling is required rather than air cooling. Figure 5 shows a diagram of a solar-operated absorption cooling system. The same collector and storage units that provide winter heating thus can provide summer cooling.

Colorado State University (CSU) house

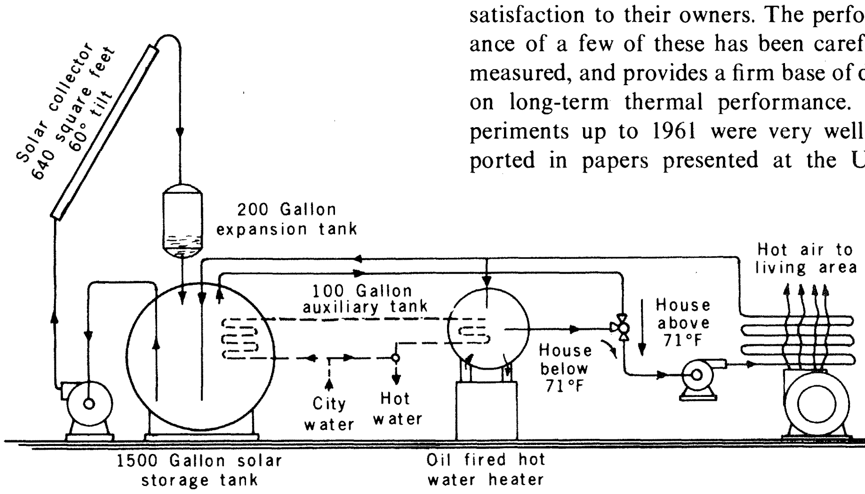


Fig. 4. Schematic diagram of the heating system in MIT house IV [adapted from Engebretson (*6*)].

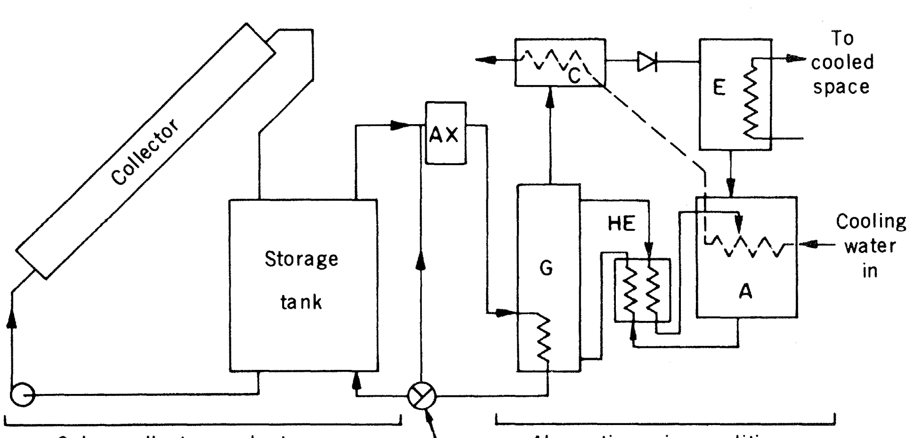


Fig. 5. Schematic diagram of a solar-operated absorption air conditioner. *AX* is the auxiliary energy source. The cooler components are as follows: *G*, generator; *C*, condenser; *E* evaporator; *A*, absorber; *HE*, heat exchanger to recover sensible heat (*18*).

I (which serves as an office building) uses a heating system that differs in some details from that of the MIT house, and also includes an absorption air conditioner. A glycol-water solution is used in the collector to avoid freezing problems and permit collector operation at higher temperatures. A heat exchanger is used to transfer solar heat into the water storage tank, and additional heat exchangers serve for heat transfer from the tank to hot water and the building. Thus, the collector supplies energy for three purposes: space heating, water heating, and air conditioning. A gas furnace provides auxiliary energy for both heating and cooling. The experiments started in August 1974 (*10*), and for the first 6 months of the heating season 86 percent of the space heating loads and 68 percent of the hot water loads were met from solar energy. Integrated performance statistics of a summer's air conditioning operation are not yet available.

A mobile laboratory (*11*) developed by Honeywell under NSF-ERDA sponsorship includes a heating and absorption air conditioning system similar to that of CSU house I. In addition, solar heat can be used to vaporize a fluorohydrocarbon which then expands through a turbine to drive a mechanical air conditioner. Thus, solar energy is converted to mechanical energy which is then used to provide cooling by conventional means. The mobile laboratory is being operated in several locations to gather data and provide a public demonstration.

In addition to closed cycle absorption cooling, open cycles are of potential interest for solar technology. For example, desiccants can be used to absorb water vapor from room air, which can then be evaporatively cooled; the desiccant is regenerated and recycled. Löf suggested the use of triethylene glycol as the desiccant, with solar-heated air for regeneration (*12*); this system is now being evaluated for use on the Citicorp Building in New York. Dunkle has designed a cycle with rotary beds of silica gel and rotary heat exchangers (*13*). In the Munters (M.E.C.) system LiCl is used as the desiccant; the system is being adapted for solar operation (*14*).

It is also possible to use a collector as an energy dissipater by designing it to lose heat by convection and by radiation to clear night sky. To accomplish this, the collector must have opposite properties to those needed for efficient collection; thus compromises are necessary or movable insulation must be used. Hay designed such a system for a clear, mild California climate. He achieves combined collector-radiator-storage capabilities in the horizontal roof of the building with movable insulation, and thereby provides heating in the winter and cooling in the summer. This system was evaluated for a year (*15*), and kept conditions inside the house within acceptable ranges throughout the period.

Another class of systems combines solar collectors and heat pumps. The heat pump can serve as an independent (auxiliary) source of heating energy, or the collector-storage system can serve as the energy source for the evaporator of the heat pump. The latter system has the apparent advantages of lowering mean collector temperature and raising the mean evaporator temperature of the heat pump (thus improving the performance of each). Systems of this type have been studied experimentally (*16*). A simulation study by Freeman compares these methods in one climate, and indicates little choice between them (*17*), but there remain many unanswered questions on how these combined systems should best be constructed and operated.

Performance Calculations

The general approach to calculating the thermal performance of solar energy systems is to write the equations that describe the performance of each of the components in a system (including collector, storage, controls, pumps, and the like, as well as the building itself), and simultaneously solve the equations, usually hour by hour. Meteorological data for the location in question, which affects both collector and building heating and cooling loads, are used as forcing functions. The solutions are time-dependent temperatures and energy rates. The energy rates can be integrated to give energy quantities over the period of the simulation. The amount of energy a system is expected to deliver over a year can then be the basis for an economic analysis. These procedures are outlined by Duffie and Beckman (*18*).

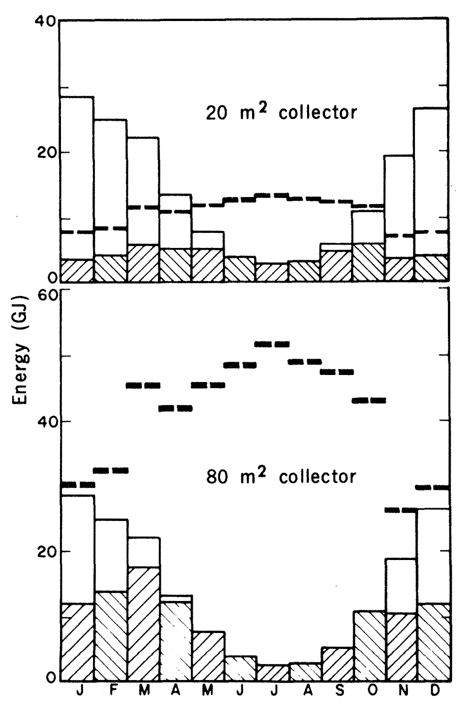


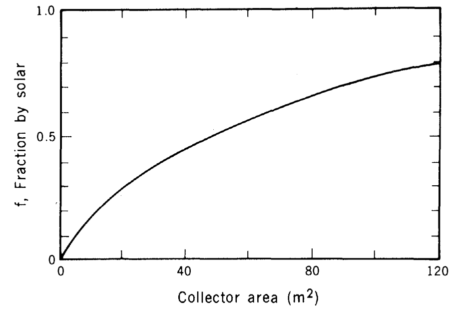
Fig. 6. Month-by-month performance of heating systems of two collector areas on a Wisconsin house with a floor area of 180 m². Incident radiation on the collector is shown by the heavy broken lines. Total heating and hot water load is inis indicated by the bars; the shaded portion represents the load met by solar, and the unshaded portion, the load met by auxiliary; *GJ*, gigajoule.

The most critical and unique component is the collector. Thanks to pioneering studies of collectors by Hottel and his colleagues, beginning almost 40 years ago and carried on by others since (*19*), methods of predicting collector performance are well established. Based on a detailed analysis, the useful gain of most collectors can be written as

$$Q_u = A_c F_R S - U_L[(T_{f,in} - T_a)]^+ = \dot{m}C_p(T_{f,out} - T_{f,in})$$

where F_R is equal to the ratio of actual energy gain to gain if the whole plate were at the fluid inlet temperature, $T_{f,in}$, and accounts for the material properties and configuration of the plate. This collector heat removal factor takes into account fluid flow rate and temperature gradients along and across the plate and enables the calculation to be made on the basis of $T_{f,in}$ (a very convenient variable). Also, A_c is the collector area, a major design parameter. S equals the absorbed radiation per unit area of collector. It is the product of incident radiation on the plane of the collector, the transmittance of a cover system, and the absorptance of the plate for solar radiation. It is a function of the orientation of the collector, the number of covers, and the properties of the covers and plate for solar radiation. The thermal loss coefficient U_L is a function of the number of covers, cover and plate properties for longwave (thermal) radiation, wind speed, and temperatures. Correlations and charts are available to determine this coefficient (*18–20*). Finally, $T_{f,out}$ is the outlet fluid temperature; T_a is ambient air temperature; and $\dot{m}C_p$ is the product fluid of mass flow rate and heat capacity. The plus sign on the bracket indicates that only positive values are taken. This simulates a controller that turns on the pump or blower whenever useful energy is to be gained from the collector, that is, when the fluid outlet temperature is higher than the inlet temperature.

Included in the equation are a wide range of design parameters and materials properties. For example, the effects of selectivity of the energy-absorbing surface,



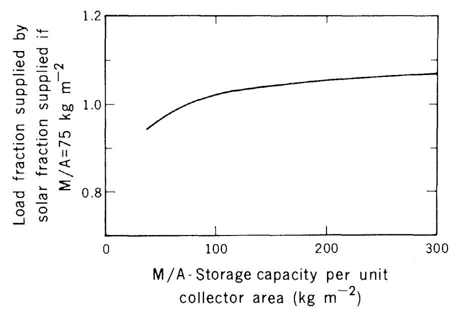


Fig. 7 (top). Variation of the fraction of the annual total load carried by solar energy with collector area for the Wisconsin example. Fig. 8 (bottom). Variation of the fraction of the annual total load carried by solar energy with storage capacity for water storage tanks.

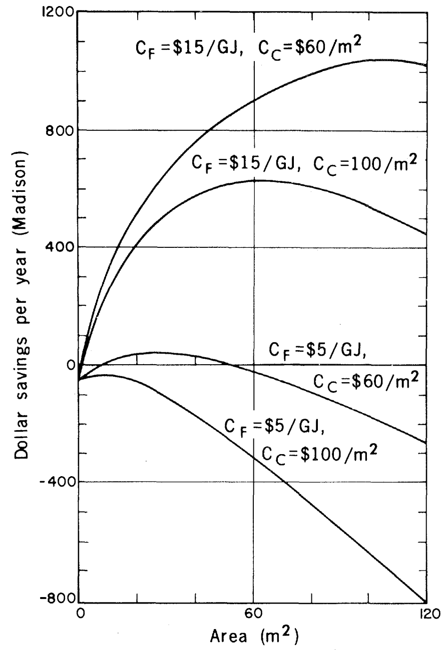


Fig. 9. Annual savings as a function of collector area for the Wisconsin example. Two collector costs and two conventional energy costs are plotted. C_F, cost of fuel; C_C, cost of collector.

that is, the absorptance of the surface for solar radiation and emittance for longwave radiation, are implicit in S and U_L.

The equation also illustrates an important determining factor in solar energy system performance. As the collector temperature ($T_{f,in}$) rises, the thermal loss term approaches the absorbed radiation term and collector output diminishes. For most practical designs today, zero output collector temperatures are typically 150° to 175°C above ambient, and normal operating temperature ranges are less than 75°C above ambient. So, collectors are uniquely sensitive to temperature and must be designed to operate at minimum temperatures above the levels required.

New collector developments are aimed at increasing absorbed radiation S and reducing thermal losses. Extensive efforts have gone into development of selective surfaces with low longwave emittances to reduce U_L (*21*). The practical problem has been to maintain desirable combinations of properties over very extended periods (20 years or more) in oxidizing atmospheres. Many of the surfaces studied are metal substrates with semiconductor coatings, for example, chrome oxide on a bright nickel base. Another approach to control of thermal losses is to evacuate the space between the absorbing surface and the cover, thus reducing or eliminating convection and conduction across the gap. This is done by enclosing the absorbing surface in tubes (*22*); elimination of convection and conduction coupled with selective surfaces of low emittances results in very low loss coefficients and allows energy delivery from collectors at substantially higher temperatures than from conventional designs.

Equations based on standard energy and materials balances, rate equations, and equilibrium relationships are available for energy storage, heat exchangers, heating and cooling loads, controls, and other components of solar energy systems. While the models of some components can be based on physical principles, it may be necessary to fall back on empirical models of coolers, heat pumps, and other complex equipment. The combination of the models of each component provides the basis for system performance calculations.

Simulations

Physical experiments on solar heating and cooling are indispensable. However, numerical experiments, such as simulations, can yield much of the same kind of information quickly and inexpensively. The effects on long-term system performance of changes in system configuration, materials properties, and component design can readily be assessed in a way that is not practical in experiments. Simulations are also useful in understanding the dynamics of systems (which never operate at steady state) and in selecting and planning experiments. We have developed a modular solar process simulation program, TRNSYS, in our laboratory, and other simulation programs have been described (*23*).

The two most obvious design variables of a solar heating system for a particular building are collector area and storage size. To see the effects of these parameters on energy delivered to a building, let us consider the following example. A house in Madison, Wisconsin, is to be provided with solar heating and hot water, from a system similar to that of the CSU experiment. The house is a typical, moderate size house with a heat loss rate corresponding to a floor area of 180 m^2 and with conventional insulation. A liquid heating collector has two glass covers, a high-absorptance, flat black paint for absorption of solar energy, and is sloped toward the south with a slope equal to the latitude (*24*). The storage tank is to be located within the building so that losses from the tank are uncontrolled gains to the building. Hot water demands are typical of a family of four or five.

The results of simulations of this system, with forcing functions of hourly weather data for an average Madison year and a fixed ratio of storage mass to collector area of 75 kg/m^2, are shown in Fig. 6. Incident radiation, total loads, and the load carried by solar energy for two collector areas are shown by months. Monthly collector efficiencies are the ratio of solar energy delivered to the building to incident solar energy on the collector; these are high when heating loads are high relative to the size of the collector, and low when loads are low. Thus, these systems tend to be overdesigned for part of the year and underdesigned for part of the year.

Annual performances, expressed as the fraction of loads supplied by solar energy, are shown in Fig. 7. Since the total loads are nearly independent of collector size, these data also indicate the total amount of solar energy delivered. These numbers are useful in deciding how much collector area should be used on the house, and indicate that very large collector areas (relative to the heating loads on the house) are needed to approach 100 percent solar heating. In other words, the larger the solar energy system, the larger the fraction of the year that it is overdesigned.

What should the storage capacity be? Figure 8 shows the effects of storage capacity on annual performance of this system. Below about 50 kg/m^2, system capacity drops off rather sharply as tank size decreases. Above 100 kg/m^2, there is a slow increase in annual performance as tank size increases. Cost studies by Tybout and Löf (*5*), and others, which take into account the cost of tanks as a function of their size, indicate that a slight cost penalty is incurred on going beyond about 100 kg/m^2.

There remains a question of seasonal storage from summer to winter. If very large storage systems were used (probably with a volume of roughly the same size as that of the heated space if heat-capacity storage is used) smaller collectors might be possible. Speyer (*25*), in 1959, concluded that this is uneconomical; reexamination of this possibility with simulation methods would be of interest.

Economics

Solar energy processes are generally capital-intensive; large investments are made in equipment to save operating costs (that is, fuel purchases). The essential economic problem is balancing annual cost of the extra investment (interest and principle, based on reasonable estimate of lifetime) against annual fuel savings. Thermal performance predictions, with estimated equipment and fuel costs, show the effects of major design decisions on annual costs.

An example of annual savings as a function of collector area, on the basis of the performance calculations noted in the previous section, is shown in Fig. 9. We assume two collector costs, $60 and $100 per square meter, and two conventional energy costs, $5 and $15 per gigajoule. Delivered energy costs in the United States today range from less than $2 per gigajoule for natural gas in the Southwest to more than $15 per gigajoule for demand electric resistance heating in some parts of the Northeast. The collector cost is the major investment and is proportional to collector area. Storage cost is only slightly dependent on collector area, and there are other equipment costs that are essentially independent of collector area. Here we have used $500 for the storage and other equipment costs and an annual charge on investment of 12 percent, corresponding to 10 percent interest over 20 years.

The curves show distinctly different behavior, with the maximum "savings" at small collector areas for the expensive collector and cheap fuel, and at a collector area of 100 m^2 for the $\$60/m^2$ collector and expensive fuel. The savings for the collector cost of $\$60/m^2$ and the fuel cost of $15 per gigajoule are positive over a range of collector areas from 10 to 50 m^2. Significant deviations from the optimum values do not greatly affect savings; thus the selection of a precise value for collector area is not very critical.

There are many assumptions inherent in these curves. Costs of taxes, maintenance, and insurance have not been included. Conventional energy costs were assumed to be fixed over the lifetime of the system. The nature of the equipment for supplying auxiliary energy (as indicated on Fig. 3) is assumed to be independent of the amount of auxiliary required during a year, while in fact it may change substantially. Costs associated with the time dependence of auxiliary energy needs are ignored; this implies that the auxiliary energy source is stored on site, since utilities could be subjected to unacceptable peak loads by large numbers of solar buildings that draw on them simultaneously only during periods of bad weather.

Nevertheless, some generalizations can be drawn from these analyses. As fuel costs rise and as the supplies of low-cost natural gas become increasingly more difficult to obtain, solar energy will become more competitive and optimum fractions of annual loads to be carried by solar energy will increase. As collector and other solar energy system costs decrease as a result of mass production, by improved technology, or by users "doing it themselves," similar improvements in the relative economics of solar energy will occur.

Finally, political decisions may be made that will affect the extent to which solar energy can be competitive. Deregulation of natural gas prices or further increases in the cost of imported oil will increase their costs to consumers and make solar energy more competitive. Tax incentives, such as write-off of investments in solar energy–producing equipment, could make an incremental improvement in solar energy economics.

Summary

We have adequate theory and engineering capability to design, install, and use equipment for solar space and water heating. Energy can be delivered at costs that are competitive now with such high-cost energy sources as much fuel-generated, electrical resistance heating. The technology of heating is being improved through collector developments, improved materials, and studies of new ways to carry out the heating processes.

Solar cooling is still in the experimental stage. Relatively few experiments have yielded information on solar operation of absorption coolers, on use of night sky radiation in locations with clear skies, on the combination of a solar-operated Rankine engine and a compression cooler, and on open cycle, humidification-dehumidification systems. Many more possibilities for exploration exist. Solar cooling may benefit from collector developments that permit energy delivery at higher temperatures and thus solar operation of additional kinds of cycles. Improved solar cooling capability can open up new applications of solar energy, particularly for larger buildings, and can result in markets for retrofitting existing buildings.

Solar energy for buildings can, in the next decade, make a significant contribution to the national energy economy and to the pocketbooks of many individual users. Very large aggregate enterprises in manufacture, sale, and installation of solar energy equipment can result, which can involve a spectrum of large and small businesses. In our view, the technology is here or will soon be at hand; thus the basic decisions as to whether the United States uses this resource will be political in nature.

References and Notes

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