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ABSTRACT

This study serves as an introduction to the important economic considerations that are necessary for an assessment of the potential for solar heating and cooling in the United States. The first chapter introduces the technology that is used to tap solar energy for residential and commercial applications and illustrates the potential significance of this energy source on a national scale. A methodology for assessing the economic feasibility of solar heating and cooling is presented in the second chapter with the results of a study of material, labor, marketing, and engineering costs of solar equipment. The third chapter applies the methodology to a study of the economic feasibility of residential solar heating in 20 cities. The potential for reductions in the cost of solar equipment through mass production and technology improvements, and the effects of increases in conventional fuel prices are included in the feasibility assessments. Finally, national security, environmental, and institutional considerations are discussed to place the economic assessment in its proper perspective. (Author)

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Solar Heating and Cooling:
An Economic Assessment

By

Arthur E. McGarity

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and International Affairs

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Washington, D.C. 20550

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preface

This study was undertaken in 1975 under support of the Office of Energy R&D Policy (OEP) of the National Science Foundation. It was recognized that there was a very considerable divergence in individual beliefs and perceptions about the economic competitiveness of solar energy for the heating or cooling of buildings and it was hoped to clarify this situation. Mr. Arthur McGarity, who was a summer intern with OEP, was asked to prepare an analytical review and summary of the published literature and the comments of authorities concerning the present and future prospects for solar energy in these applications. The complexities of the question prevented quick treatment, and Mr. McGarity continued the inquiry under NSF support when he returned to his graduate studies in Systems Analysis and Economics for Public Decision Making, a program of the Johns Hopkins University Department of Geography and Environmental Engineering.

The draft report which resulted was circulated for review to experts in and out of government, ranging from solar energy enthusiasts to skeptics. Their comments and criticisms helped produce an improved document of enlarged scope. The final product thus benefited from many inputs, but the most significant was Mr. McGarity's own. Those of us who worked with him have greatly appreciated his diligence in pursuing an objective treatment of this important subject.

Glen A. Graves
Senior Policy Analyst
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acknowledgment

The author would like to acknowledge others who have made important contributions to this study. Steve Rattien, Len Topper, and Paul Donovan of the former NSF Office of Energy R&D Policy stimulated the original research. Fred Orthlieb, also formerly with OEP, helped with the analysis of the initial results; and Glen A. Graves of the NSF Division of Policy Research and Analysis (PRA) provided for a continued analysis and assessment of the results. Ronald M. Powell, also of PRA, has been especially helpful with his comments and assistance in the publication of this work. Many analysts and manufacturers in the solar heating and cooling field have provided useful information and comments on early drafts.

I would also like to thank those who helped with the preparation of the final draft: Glen A. Graves, Thomas and Cathline McGarity, Ronald M. Powell, and Jane Ziegler. Derrick Coleman did the excellent graphics work.

Arthur E. McGarity

summary of content, results and conclusions

This study serves as an introduction to the important economic considerations that are necessary for an assessment of the potential for solar heating and cooling in the United States. The first chapter introduces the reader to the technology that is used to tap solar energy for residential and commercial applications and illustrates the potential significance of this energy source on a national scale. A methodology for assessing the economic feasibility of solar heating and cooling is presented in the second chapter with the results of a study of material, labor, marketing, and engineering costs of solar equipment. The third chapter applies the methodology to a study of the economic feasibility of residential solar heating in 20 U.S. cities. The potential for reductions in the cost of solar equipment through mass production and technology improvements, and the effects of increases in conventional fuel prices are included in the feasibility assessment. Finally, national security, environmental, and institutional considerations are discussed to place the economic assessment in its proper perspective.

The primary result of the study is the 20 U.S. city cost comparison of solar space and hot water heating (combined) with conventional space and hot water heating in detached residences. Geographical variations in conventional fuel costs and solar heating system performance are considered, although geographical variations in solar equipment and installation costs are neglected. The solar cost data are obtained primarily from private producers of solar heating systems, and the conventional heating cost data are obtained from suppliers of conventional energy (natural gas, oil, and electricity) in each of the 20 cities. Solar equipment annual performance estimates for each city are obtained by combining climatic data with equipment characteristics as input to a simulation model developed at the University of Wisconsin.

Comparisons are made using three sets of costs for solar collectors and heat storage equipment. The first set, called Case I, uses costs that were estimated for systems built in 1975. Two cost reduction scenarios are applied to adjust the Case I numbers to obtain the other two sets. The first cost reduction scenario, called Case II, accounts for the mass production of collectors in a competitive market situation. The second cost reduction scenario, called Case III, accounts for mass production of collectors and technology improvements that increase the efficiency of collectors and reduce the amount of materials required in the collectors.

The cost of fuel for conventional space and hot water heating is conveniently expressed on a cost per unit of energy basis in dollars per million BTU of heat energy. The cost of solar collectors and heat storage equipment can also be calculated on this basis for comparisons. This is done by computing uniform annual costs for the solar equipment based on a 20 year equipment lifetime and an interest rate of eight percent. The performance model determines the amount of heat energy that is delivered by the solar equipment to a home in each of the 20 cities during a typical year. The cost of solar energy is found by combining cost and performance estimates.

Unlike solar energy, the cost of conventional energy is subject to fuel price increases due to inflation and "real" price increases. To account for conventional fuel price increases, the cost comparisons in this study incorporate an annual fuel price increase of 5 percent during the 20 year lifetime of the solar equipment. It may be that inflation alone will be responsible for such increases during the next 20 years. "Real" fuel price increases due to the depletion of conventional fuels will improve the comparisons in favor of solar heating.

The results of the cost comparisons show that with no "real" increase in conventional fuel prices, the installation of solar heating instead of electric resistance heating can result in savings in 5 out of 20 cities with Case II costs and performance and in 13 out of 20 cities with Case III costs and performance. Also, it is shown that Case III solar heating is competitive with oil heating in one out of 8 cities. If an 8 percent, 20 year loan can be obtained for the purchase of the equipment, the savings can be realized on a monthly basis when mortgage payments are compared with the monthly fuel bills for a conventional heating system. These savings may not occur immediately; but they will occur at a sufficiently early time so that the capital cost and financing charges for the solar equipment are repaid at some time before the 20 year loan term expires.

Moreover, if a 2 percent "real" increase in the cost of conventional energy occurs each year, Case II solar heating is competitive with electricity in 9 out of 20 cities. Also, Case III solar heating is competitive with electricity in 17 out of 20 cities, with oil in 3 out of 8 cities, and with natural gas in 1 out of 20 cities.

This study contributes a methodology based on sound principles of engineering economics to the search for an analytic procedure for evaluating the economic potentials of solar heating and cooling. Applying the methodology to solar heating in 20 U.S. cities shows that there may be considerable potential for the tapping of this energy source by economically prudent home owners. However, the final assessment of economic feasibility is critically dependent on assumptions about the cost and availability of conventional sources of fuel. The true potential for solar energy will be known only when more certainty exists concerning the future of conventional energy.

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CONTENTS

CHAPTER 1

Introduction to Solar Heating and Cooling

Interest in the utilization of renewable forms of energy in the United States has increased with our Nation's increasing dependence on foreign sources of nonrenewable petroleum. Depletion of domestic petroleum and the recognition of environmental problems associated with the utilization of conventional energy sources, has induced a search for renewable, nonpolluting energy supplies. The sun's radiation, absorbed by a collector apparatus and converted into low temperature (100°-200° Fahrenheit) heat, is one source of energy that is both renewable and nonpolluting. Installation of the proper equipment on a home or commercial building enables the use of solar energy in this form for domestic water heating and for room heating and cooling.

Equipment for these applications of solar energy is currently available and demonstrations have proved that buildings can be heated in most sections of the country and both heated and cooled in many others (1). Since water heating, space heating, and air conditioning are responsible for about 25 percent of the Nation's total energy demand, the installation of such equipment on a large percentage of the country's buildings would significantly reduce demands for conventional fuels (2). Environmental disruptions are limited to those associated with obtaining and processing the raw materials such as copper and aluminum from which solar equipment is built. Thus, it appears that the rapid proliferation of solar heated and cooled buildings may help to solve two problems: that of maintaining an adequate energy supply and that of reducing environmental pollution. It is important to note that these two problems often generate conflicting solutions.

However, an evaluation of solutions to energy problems is not complete without economic considerations. In this area serious doubts arise concerning the true potential for this energy source. The owner of a home or small business establishment faces an investment of several thousand dollars for solar heating and cooling. In a new building, this equipment can be incorporated into the design, and payment can be included in the financial arrangements for the entire building. Installation of equipment on an existing structure (retrofitting) is usually accomplished at a higher price due to the costs of modifications to the original climate control system and building architecture.

Solar heating and cooling is called "economical" in this study when the costs associated with it are less than the costs of using an alternative conventional fuel. For simplicity, natural gas, fuel oil, and electricity are called "conventional fuels." The "alternative conventional fuel", or simply "alternative fuel", is the conventional fuel which competes most successfully against solar energy. In most parts of the United States the alternative is either natural gas, fuel oil, or electricity depending on price, availability, and the preferences of the builder or the building owner. In order to determine if the installation of solar equipment on a certain type of building in a particular location is economical, the price of the alternative fuel must be known, and price fluctuations have made it very difficult to predict the future cost of fuels.

There are a number of factors that affect the price of conventional fuels. One important influence is inflation which causes the price of all goods to increase as the purchasing power of the dollar decreases. Another factor is the scarcity caused by the depletion of nonrenewable fossil fuels which also causes increases in fuel prices. A third cause of price fluctuations is the erratic nature of international politics which causes the prices of imported fuels to vary in both directions.

A major advantage to the installation of a solar energy system is a degree of isolation from the uncertainties of fuel price fluctuations. After solar equipment has been purchased and installed, solar energy is delivered to the building free of charge and independent of fuel price increases. The cost of the auxiliary energy required during cloudy weather is the only major cost that is subject to change.

Technical and economic feasibilities are necessary, but not sufficient conditions for the occurrence of widespread solar energy use. Institutional barriers sometimes exist that prohibit the installation of the least expensive systems or add to the financial burden of purchasing and operating the equipment. Examples are zoning regulations that restrict the height of structures and property taxes on solar additions which may add substantially to the annual cost of heating and cooling a building. Institutional arrangements can be modified, though, to eliminate barriers and, in some instances, to encourage the public to utilize solar energy. For example, this can be done through the provision of economic incentives or by restricting the use of conventional fuels (3,4).

Scope of Study

Focus

The primary focus of this study is on the economics of solar heating and cooling. In addition, technical aspects and institutional considerations are treated in order to place the economic analysis in its proper perspective. It is important to emphasize that this study does not attempt to predict the future success or failure of the solar heating and cooling industry. Such an effort would require knowledge of the future price fluctuations of conventional fuels, and the author does not wish to become embroiled in the controversy surrounding the various predictions of future fuel prices.

Contribution

The major contribution of this study is a detailed assessment of the costs involved in heating and cooling a single family residence with solar energy. Actual 1975 costs are discussed as well as the costs which can be expected with mass production of flat plate collectors and with advanced collector designs. In addition, a methodology is presented that enables the comparison of an investment in solar equipment with an investment in conventional equipment. The approach is called "life-cycle cost analysis," and it relies heavily on the principles of engineering economics. It enables the comparison of solar energy with conventional fuels on the basis of dollars per unit of energy.

Although the methodology is general and can be used to treat both heating and cooling, only solar heating is treated with enough detail for an accurate assessment. The information on the cost and performance of solar cooling systems is currently too sketchy to enable more than a hypothetical guess concerning the performance to be expected and a rough estimate of the costs involved.

The results of this analysis of solar costs, when combined with information on the current cost of conventional fuels, serve as initial conditions for an analysis that compares the economics of solar energy with the economics of conventional energy sources. It is important to note that the price of solar energy is determined through essentially free market interactions while the prices of conventional fuels result from a high degree of government regulation. When predictions are made—concerning future inflation rates, conventional fuel price fluctuations that occur in addition to inflation, and changes in government policy—comparisons can be made; but their accuracy is no greater than the accuracy of the predictions. A variation of this approach is to treat government policy as a variable and to test the effects of different policies on the comparisons. This study supplies a methodology and a set of initial conditions which enables the reader to make such comparisons.

Chapter Summaries

The current chapter introduces the reader who is unfamiliar with this use of solar energy to the technical fundamentals. This study deals only with those systems that use the sun's radiation to heat directly a fluid and that utilize the collected energy at rather low temperatures employed for space heating and for powering heat driven cooling apparatus.

The analysis does not include solar-electric systems for homes which use photovoltaic cells or generators driven by heat engines. Photovoltaic conversion of solar energy is presently more expensive and less efficient than thermal conversion. Heat engines usually require higher temperatures which may be obtained by using focusing collectors that track the sun as it moves across the sky. Low temperature collectors use a simpler and less expensive flat plate which can be mounted in a fixed position. Research efforts are being directed toward improving the efficiency and reducing the cost of solar-electric systems, but most of the work is concerned with large scale centralized generating facilities (5).

To acquaint the reader with the possible contribution that solar heating and cooling of buildings can make to the total energy requirements of the United States, the first chapter also presents an overview of energy use in residential and commercial buildings. Three hypothetical levels of solar heating and cooling development are examined to determine their significance on a national scale.

The second chapter is a discussion of the important factors that comprise an economic analysis of solar heating and cooling. The principles of life-cycle cost analysis are presented, and a method is described for expressing the cost of solar energy on a dollar per unit of energy basis. Estimated 1975 material, labor, engineering, and marketing costs for a solar heating system on a single-family residence are presented as derived from a survey of demonstration projects, equipment producers, and other studies. Performance characteristics of solar heating and cooling systems are set forth, and the use of simulation models to predict performance is described. One such performance model, recently developed at the University of Wisconsin, is used to generate performance curves for a solar heating system supplying room heat and domestic hot water to a single-family detached residence in a variety of geographical locations(6).

Cost information and performance curves are combined to create curves that show the variation of cost per unit of solar energy with the size of the system. It is then shown how the cost of solar energy can be compared with the cost of other more conventional fuels. Furthermore, consideration is given to the proper sizing of a system so that it supplies heating and cooling to a building at the minimum cost. Finally, it is shown that when assumptions are made concerning changes in the prices of conventional fuels, life-cycle cost analysis can be applied to determine if a cost savings will result over the lifetime of the solar equipment.

The final chapter applies the method of analysis developed in the second chapter to solar heating in the United States. Also, an example is constructed to show how the analysis can be applied to combined heating and cooling. In the heating analysis, 20 U.S. cities are chosen for an economic comparison of solar heating with conventional heating methods.

The comparisons are made for 1975 solar costs and for two solar cost reduction scenarios which presume savings from mass production and advanced collector design. The costs of conventional fuels are projected from 1975 costs with adjustments for inflation. In locations where solar heating is not cost competitive with conventional heating, the fuel price increase necessary to bring about a competitive situation is shown. Also, three cities are selected for a detailed analysis of the optimal sizes and of the corresponding capital and annual costs of solar heating systems.

The final section of the third chapter discusses institutional factors which may either inhibit or encourage growth. In addition the noneconomic benefits of significant solar development are discussed.

Technical Fundamentals

Solar heating systems generally consist of four major parts: a collector, a storage unit, an auxiliary unit using a conventional fuel, and a distribution system. Solar cooling systems are essentially the same with the addition of a cooling unit powered by solar heat energy. The auxiliary unit and distribution system are

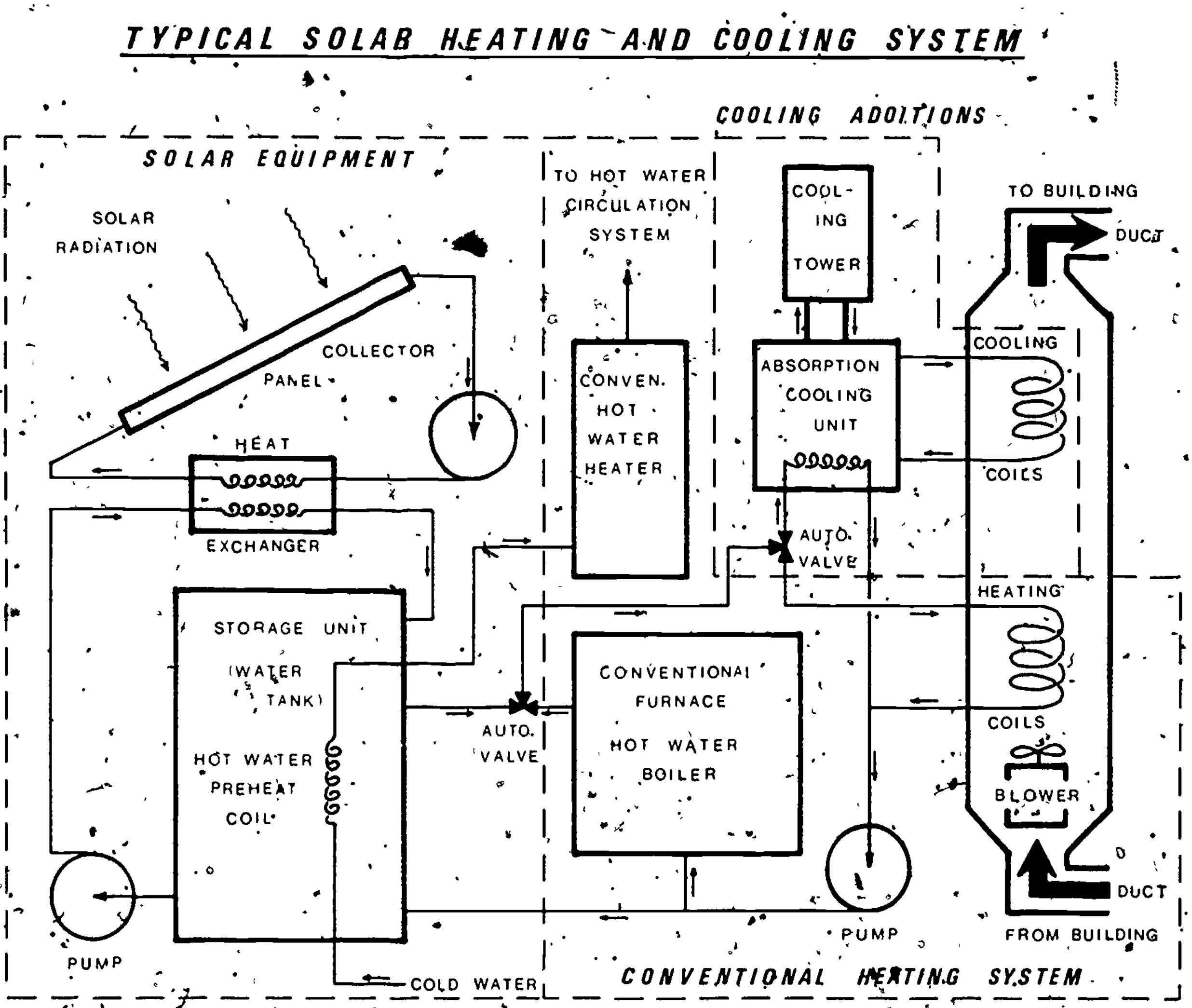


Figure 1. Typical solar heating and cooling system using water as the collector circulation fluid and a water tank for heat storage. The conventional furnace operates in a parallel mode with the collector and storage unit.

usually the same as equipment used in a conventional heating and cooling system. A schematic diagram of a typical combined heating and cooling system is shown in Figure 1. Many variations are possible. The sun's energy arrives in the form of radiation at frequencies in and around the visible light spectrum. The amount of energy reaching the surface of the earth is dependent on the geographic location, the time of year, the time of day, and weather conditions.

Collectors

The most common type of collector uses a flat metal plate to absorb the radiation. A coating surface (usually flat black paint) is incorporated with the plate to allow maximum absorption of the sun's rays. When the plate's temperature begins to rise, heat energy is removed from the plate by passing a fluid over the plate or through tubes connected to the surface of the plate.

The plate is mounted in a panshaped enclosure with one or two sheets of glass above the plate allowing light to pass through and reducing heat loss due to infrared radiation and the cooling effects of wind. Insulating material installed below the plate reduces heat loss to the supporting structure. Several collector modules are connected and mounted together in a panel assembly sized to provide the desired amount of heat energy.

Because the United States is located in the Northern Hemisphere, the sun is found in the southern sky during most of the year. Thus, the collector surface must face the south and be tilted at an angle to the horizontal. When the solar system is included in the design of a new

FLAT PLATE COLLECTOR DESIGN

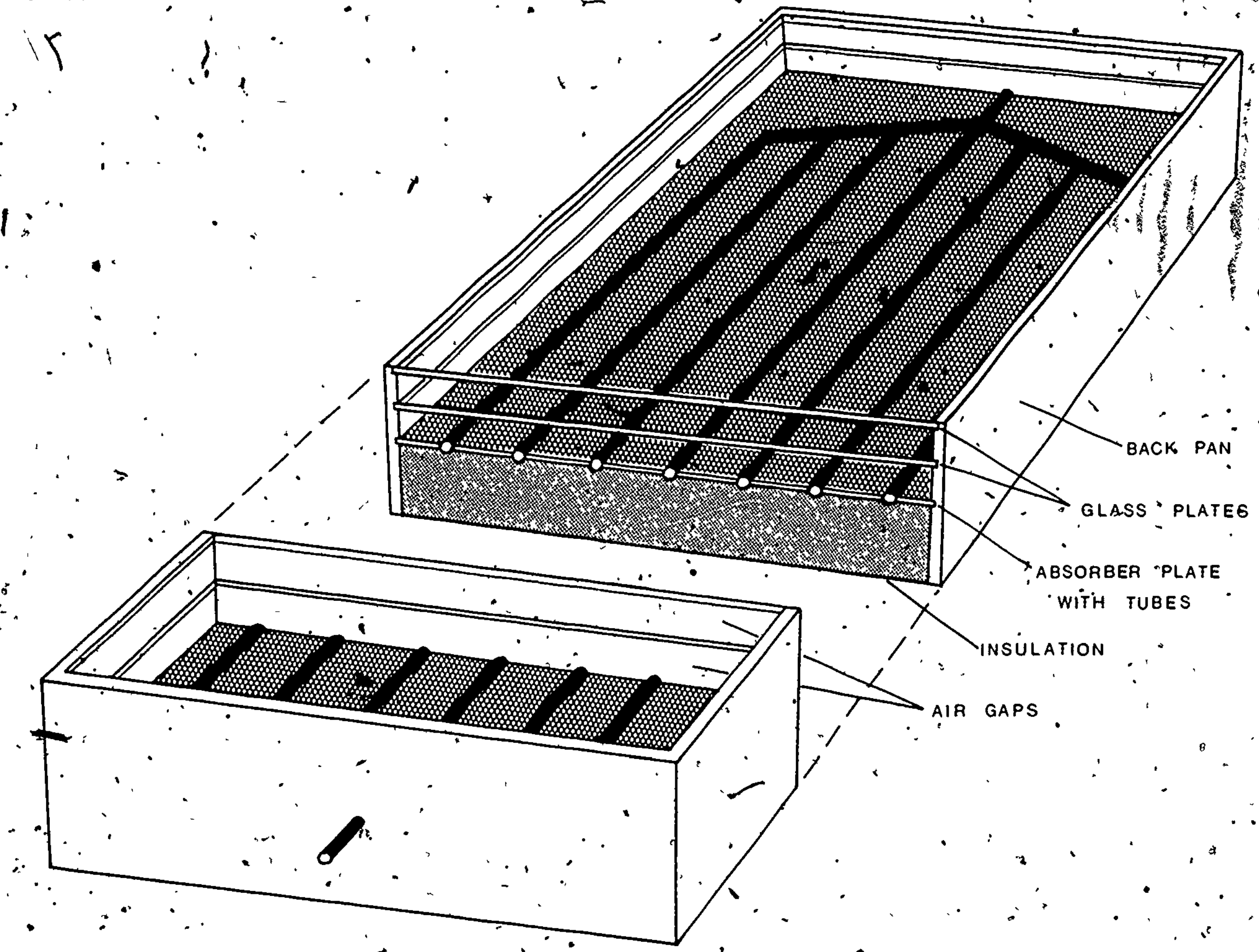


Figure 2. Flat plate collector design for a water type collector The water tubes are fabricated in the collector plate.

building, part of the roof can be replaced by the collector assembly and the roof slope can be made to correspond to the proper collector tilt.

Both liquids and gases are appropriate for use as heat collection and distribution fluids. Water is the commonly used liquid and air is that commonly used gas. The system shown in Figure 1 uses water. Water systems use collectors with tubes fastened to the plate or shaped in the plate by a fabrication technique. One design of this type is illustrated in Figure 2. Corrosion inhibiting chemicals are added to the water, and freezing is avoided by adding antifreeze or by draining the collectors whenever freezing temperatures occur. A pump driven by electricity is usually necessary to circulate the water through the collector and the connecting piping. When air is used to collect the heat, a blower forces the air through connecting ductwork into the collector and over the surface of the plate. Finned or honeycombed projections on the plate can be used to increase heat transfer to the circulating air.

Storage

Storage of solar energy is necessary to provide heating and cooling during nights and on days with significant cloud cover. Heat collected in water systems can be stored by holding a large quantity of the heated water in an insulated tank.

Water is well suited for this purpose because of it's high heat capacity. An inexpensive method of storing the heat collected in air systems uses an insulated bed of roughly equally sized pebbles through which the air is passed. The creation of temperature "layers" in the storage unit (temperature stratification) can be produced in pebble beds, increasing the efficiency of the system.

Auxiliary Energy and Distribution Systems

Economic considerations usually require that the solar system be sized to provide less than 100 percent of the year's heating and cooling requirements. Many locations experience winters with long periods of very low temperatures accompanied by low quantities of insolation (incident solar radiation). During these periods a conventional energy source must supply energy. Equipment sized to fully accomodate these extreme circumstances is simply too costly. Conventional heating equipment is used in an auxiliary mode to supplement the solar equipment. For domestic hot water a conventional hot water heater can be used to boost the temperature of the solar heated water. For space heating, electric resistance heating, a heat pump, or a natural gas or oil furnace can be operated in parallel with the solar equipment. Also, the absorption cooling unit can be designed for operation from the energy in heated water supplied by the solar equipment or from heat obtained from conventional energy source.

The heating distribution system can make direct use of the elevated temperature of either the collector's circulating fluid or the storage unit. In water systems hot water from the collectors or the storage unit is circulated through a network of room radiators or through coils over which air is blown for distribution in ductwork. In air systems heated air from the collector or from storage is blown directly into the rooms through a system of ducts. In both systems hot water for domestic use is heated by passing the water through a heat exchanger which transfers heat from the circulating fluid or from storage.

Cooling

The cooling system consists of a heat powered air conditioner similar to cooling units powered by the combustion of natural gas. These "absorption type" air conditioners require temperatures of at least 180° F for operation, while heating requires temperatures around 120° F. The requirement for higher collection and storage temperatures for cooling usually dictates that a water system be used. Air collection and pebble bed storage is not reliable for the supply of heat at temperatures greater than 150° F. However, in dry climates where air conditioning by dehumidification and evaporation is sufficient to meet cooling needs, lower temperature solar heat can be used to aid the operation of an evaporative cooler. Another technique used in dry climates operates by chilling water at night by radiation to the cool night sky. The water is stored and used for cooling the next day.

Typical Operation

Operation of the heating and cooling system requires a system for controlling the interactions of the four major parts. Variations in heating and cooling loads and in the amount of available solar energy impose the need for different operating modes. When sunshine is plentiful and the load is low, collected energy is stored until the capacity of the storage unit is reached. If the load is high during a period of cloud cover, heat is withdrawn from storage until it is depleted and auxiliary energy is required. A control system utilizing temperature sensors and relays or electronic switching apparatus can automatically operate the components, maintaining the inside temperature at the desired level as set by a thermostat.

Figure 3 illustrates the operation of a residential solar heating system during a typical 3 day period in the winter. The first day is characterized by a partly cloudy morning and a clear afternoon with mild temperatures throughout the day. The heating load is low and solar energy is available in quantities large enough to meet the entire load and charge the storage unit to full capacity. After the storage unit is fully charged, additional incident solar energy is necessarily wasted. During the night of the first day, unusual weather activity, such as the arrival of a cold front, lowers temperatures and the heating demand increases. Heat stored during the day is withdrawn from the storage unit to maintain constant temperatures indoors.

The second day is partly sunny with continued

Solar Heating System Operation

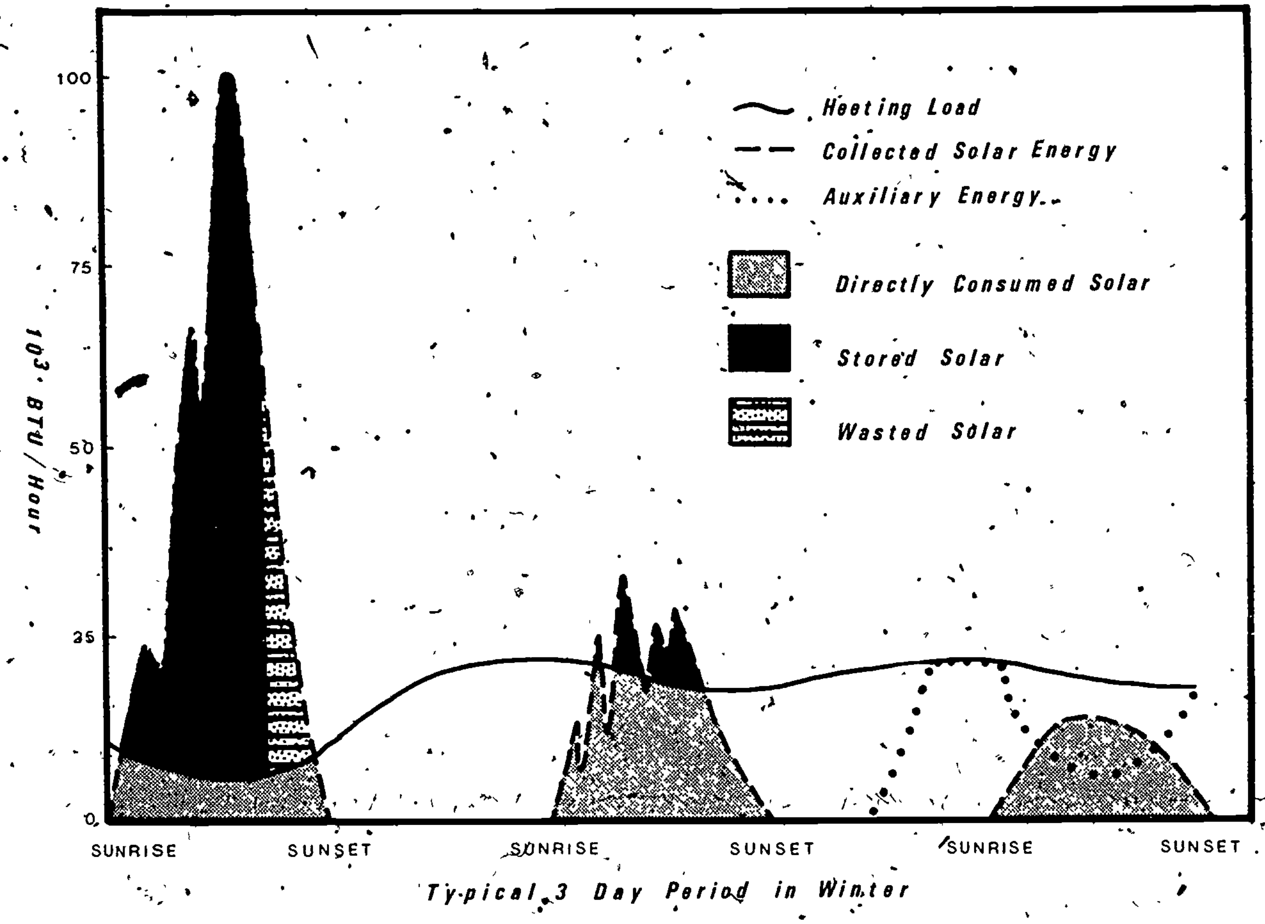


Figure 3. Solar heating system operation. All modes of operation are displayed.

low temperatures. Solar energy supplies the entire heating load during most of the day and adds a small amount of heat to storage. During the night of the second day, the energy in storage is depleted and the auxiliary unit must supply the entire load. The third day is mostly overcast with low temperatures, and the solar energy is not sufficient to meet the load. The auxiliary unit is used to supply varying portions of the load throughout the day.

The components and system described above use fairly unsophisticated technology and no improvements are necessary to provide a dependable working system. However, several design improvements can be made to increase the efficiency of energy collection. Collector plate coating surfaces, called selective surfaces, are being developed which absorb most of the incident radiation but reradiate almost none of the absorbed energy.

A totally different collector design has the absorptive surface and fluid flow tubes enclosed in an airtight glass cylinder. A vacuum is created in the interior of the cylinder, substantially reducing heat losses to the surrounding air and making the collector more efficient at the high temperatures required for cooling. Manufacturers of this type of collector are hopeful that production techniques similar to those used to make fluorescent lamps and vacuum tubes can be used to produce the cylindrical collectors at low cost. It is also hoped that the amount of metal in the collector surface can be reduced by using recently-developed advanced heat transfer technology such as that in "heat pipes" (7).

This section has briefly reviewed the technical aspects of heating and cooling with solar energy.

A more rigorous and detailed treatment of technical fundamentals can be found in Chapter 59 of the *1974 Applications Volume* of the American Society of Heating, Refrigerating, and Air Conditioning Engineers recently compiled by John Yellott with the support of the National Science Foundation RANN Program (8).

Growth Scenarios

The quantity of energy used by the Nation for solar heating and cooling applications is closely related to the heating and cooling energy demand of residential and commercial buildings. In addition, the rate of growth of this energy demand due to the construction of new buildings is important because solar equipment is more easily incorporated into the design of new buildings than installed in existing buildings. Figure 4 shows the total space heating, domestic hot water, and air conditioning energy requirements, for residential and commercial buildings in the United States in 1970 with a projection of requirements for 1990. The figures for both years are taken from the Federal Energy

Residential and Commercial Energy Use
1970 and 1990

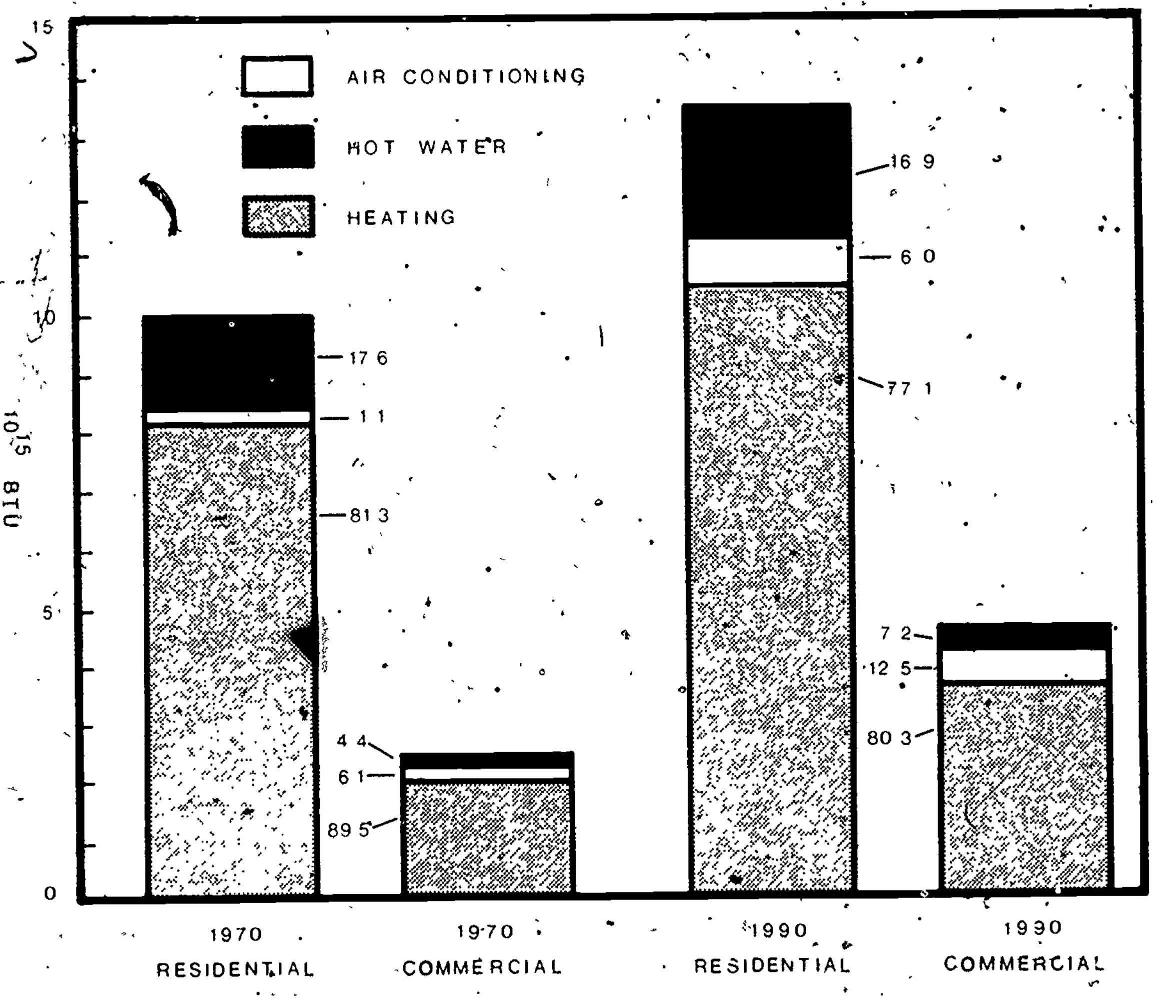


Figure 4. Display of residential and commercial energy use in 1970 and 1990 (Source Project Independence See reference 9.)

Administration's Project Independence report base case projections (9). It is seen that space heating and hot water are responsible for the greatest portion of the load, whereas air conditioning (cooling) is responsible for only a small portion in both years.

Studies have shown that combined solar heating and cooling installations are sometimes more cost effective than heating or cooling installations alone (10). This is because the collector and storage unit can be used during the entire year in many locations. However, the significance of this fact is diminished on a national scale by the information displayed in Figure 4. It shows the small size of the cooling load in relation to the total energy used for climate control and domestic water heating. Cost studies describing the economies associated with combined heating and cooling must be taken into account in light of the fact that many residences and commercial establishments in the United States currently require little or no energy for space cooling purposes. Nevertheless, the 1990 projection indicates that the demand for air conditioning and the corresponding potential for solar cooling development may increase to a significant level. It is also important to note that most of this load occurs in the southern and western States where summer sunshine is plentiful. In these regions widespread use of solar cooling might help to alleviate the peak loading problems of electric utilities caused by electric air conditioners (11). The potential for this type of benefit is obscured when national, rather than regional energy consumption figures are considered.

Table 1 describes the significance of various degrees of solar energy utilization under three hypothetical scenarios of introduction and growth. The numbers in the table are calculated from information in Figure 4 using the listed set of assumptions for each scenario. Scenario I, involving only new construction, is technically feasible and may be economically feasible if the cost of solar equipment becomes competitive with conventional fuel costs. Scenario II illustrates the large increase in solar utilization that is possible with a very small percentage of retrofit applications. Scenario III shows the intense degree of solar development which would be required to supply a large portion of the heating and cooling load by 1990. This level of development (5.5 x 10^{15} BTU/year from solar heating and cooling) might require the installation of some 40 to 60 million solar units on residential and commercial buildings by 1990.

Table 1: Use of Solar Heating and Cooling Three Hypothetical Growth Scenarios for U.S.

	1990 Energy from Solar (10^{15} BTU/Year)	% Of Total 1990 Energy for Heating & Cooling	% Of Total 1990 U.S. Energy Demand
Scenario I	0.28	1.4%	0.4%
Scenario II	0.91	4.7%	1.2%
Scenario III	5.5	28.4%	7.1%

Scenario I—*No retrofit New solar installations* supply 5% of 1970-1990 growth in hot water and space heating load and 1% of 1970-1990 growth in air conditioning load.

Scenario II—*Solar retrofits* installed to supply 5% of 1970 hot water and space heating load and 1% of 1970 air conditioning load by 1990 *New solar installations* same as Scenario I

Scenario III—*Solar retrofits* supply 25% of 1970 hot water and space heating load and 10% of 1970 air conditioning load by 1990 Also *new solar installations* supply 10% of 1970-1990 growth in space heating and hot water load and 15% of 1970-1990 growth in air conditioning load

Other Assumptions

1) The numbers are based on Fig 4 which is for *end use* consumption 2) It is assumed that the heating and cooling load will continue to make up 25% of the total U S energy demand in 1990

CHAPTER 2

Solar Heating and Cooling Economics

An economic assessment of solar hot water heating and space conditioning equipment can be accomplished using techniques similar to those used in the analysis of any project requiring a large capital investment. This "capital intense" aspect of solar equipment is in sharp contrast to conventional systems which have a much lower initial cost for equipment and a rather high operating cost for fuel throughout the lifetime of the equipment. An accurate comparison of solar equipment with conventional equipment must consider all costs associated with the purchase, installation, and lifetime operation of both types of equipment. Consequently, the well established techniques of engineering economics are beginning to be applied as "life-cycle cost analysis" to comparisons of solar with conventional equipment (12, 13).

Life Cycle Cost Analysis

A life-cycle cost analysis gathers expenses that occur at different times into one cost number that can be used to compare alternatives. There are two schemes for grouping costs that yield the same result when comparisons are made. One is the "present value method" which treats all costs occurring throughout the lifetime of the equipment as if they could be paid at the present. The other approach is the "annual cost method" which treats these costs as if they occurred in even annual payments during the equipment's lifetime. This method is especially useful for a heating and cooling cost study because the annual cost divided by the amount of energy supplied during a year yields an estimate of the average amount paid for each unit of energy.

When the costs that actually do occur on an annual basis (such as fuel and maintenance costs) do not change from year to year, both methods are straightforward and either approach is sufficient for making comparisons. However, when annual costs are expected to vary each year due to changing prices, the present value of these costs must be calculated before a uniform annual cost figure can be computed. Thus, since fuel prices are of a changing nature, it is important to understand both the present value and the annual cost approaches for a comparison of solar with conventional heating and cooling.

Both methods assign a greater value to expenditures made at the present than to those made sometime in the future. This priority occurs because one dollar received at the present is equivalent to more than one dollar received a year later since the first dollar can be invested to collect interest. In fact, it can be observed that money has a "time value" to a consumer and that this value is associated with the interest one must pay on a loan. The interest rate paid by a consumer actually consists of three components: a percentage reflecting the consumer's time value of money, a percentage accounting for the risk incurred by the lender, and a percentage determined by the lender's estimate of the average inflation rate during the load period (14, 15).

Present Value Method

The present value method accounts for the time value of money by multiplying costs occuring in future years by a fractional discounting factor which is made smaller each year. These reduced annual costs are added together to obtain a single number that is equal to the present value of the future annual expenditures. This number represents the amount that could be invested at interest in the present to yield the amount necessary to pay all of the future annual costs as they occur. Thus, the present value is less than the sum of all the future annual costs. The present value of the entire investment is calculated by adding, the initial purchase and installation expenses, which actually do occur at the present, to the present value of future annual costs.

The factor used to reduce the future annual costs is determined by a number called the discount rate (d) which has the same value as the relevant interest rate. Annual costs are reduced in the first year by $1/(1+d)$, in the second year by $1/(1+d)^2$, in the third year by $1/(1+d)^3$, and so on. Thus when annual costs are constant each year, the present value of these costs is calculated by the formula 1:

$$\begin{aligned}\begin{pmatrix}\text{PRESENT}\\\text{VALUE}\end{pmatrix} &= \begin{pmatrix}\text{CONSTANT}\\\text{ANNUAL}\\\text{COSTS}\end{pmatrix} \times \left(\sum_{j=1}^{n} 1/(1+d)^j\right)\\ &= \begin{pmatrix}\text{CONSTANT}\\\text{ANNUAL}\\\text{COSTS}\end{pmatrix} \times \frac{1}{d}\left[1-\left(\frac{1}{1+d}\right)^n\right]\end{aligned} \qquad [1]$$

Where n is the lifetime of the equipment (12).

When annual costs are expected to increase with time, an additional factor must be used to account for this increase. When the fractional annual increase in such a cost is denoted by e, the initial annual cost is increased by a factor of $(1+e)$ in the first year, by $(1+e)^2$ in the second year, by $(1+e)^3$ in the third year, and so on. Thus the present value formula becomes formula 2:

$$\begin{pmatrix}\text{PRESENT}\\\text{VALUE}\end{pmatrix} = \begin{pmatrix}\text{INITIAL}\\\text{ANNUAL}\\\text{COSTS}\end{pmatrix} \times B$$

$$\text{where } B = \sum_{j=1}^{n} \left(\frac{1+e}{1+d}\right)^j = \frac{1+e}{d-e}\left[1-\left(\frac{1+e}{1+d}\right)^n\right] \qquad [2]$$

unless e is equal to d, and in this case B is equal to n (13). The present value of the entire investment is found by adding the appropriate present value of annual costs to the initial purchase and installation expenses as in formula 3:

$$\begin{pmatrix}\text{PRESENT VALUE}\\\text{ENTIRE}\\\text{INVESTMENT}\end{pmatrix} = \begin{pmatrix}\text{INITIAL}\\\text{EXPENSES}\end{pmatrix} + \begin{pmatrix}\text{PRESENT VALUE}\\\text{ANNUAL}\\\text{COSTS}\end{pmatrix} \qquad [3]$$

Annual Cost Method

The annual cost method accounts for the time value of money by treating the present value of the entire investment as if it will be financed by a loan with compound interest and no down payment. The uniform annual payment for this arrangement is found by using the uniform capital recovery formula:

$$\begin{pmatrix}\text{UNIFORM}\\\text{ANNUAL}\\\text{COST}\end{pmatrix} = \begin{pmatrix}\text{PRESENT VALUE}\\\text{ENTIRE}\\\text{INVESTMENT}\end{pmatrix} \times \left(\frac{r(1+r)^n}{(1+r)^n-1}\right) \qquad [4]$$

where r is the interest rate and n is the lifetime of the equipment (12).

Since the uniform annual cost depends on the results of the present value analysis, the formulas for present value can be used to simplify formula 4. One simplification arises from the fact that the time value of money is the same for both methods. Thus, d is equal to r. Again there are two cases involving actual annual costs for fuel and maintenance. First, when annual costs remain constant from year to year, formula 4 becomes:

$$\begin{pmatrix}\text{UNIFORM}\\\text{ANNUAL}\\\text{COST}\end{pmatrix} = \left[\begin{pmatrix}\text{INITIAL}\\\text{EXPENSES}\end{pmatrix} \times \left(\frac{r(1+r)^n}{(1+r)^n-1}\right)\right] + \begin{pmatrix}\text{CONSTANT}\\\text{ANNUAL}\\\text{COSTS}\end{pmatrix} \qquad [5]$$

Formula 5 can be better understood by thinking of the uniform annual cost as being the amount one would pay each year towards repaying a loan made to purchase the heating and cooling equipment plus the cost of fuel and maintenance for one year.

Finally, when annual costs are expected to increase by a fractional amount each year, formulas 2, 3, and 4 are combined to yield formula 6:

$$\begin{pmatrix}\text{UNIFORM}\\ \text{ANNUAL}\\ \text{COST}\end{pmatrix} = \left[\begin{pmatrix}\text{INITIAL}\\ \text{EXPENSES}\end{pmatrix} \times \left(\frac{r(1+r)^n}{(1+r)^n-1}\right)\right] + \left[\begin{pmatrix}\text{INITIAL}\\ \text{ANNUAL}\\ \text{COST}\end{pmatrix} \times D\right]$$

$$\text{where} \quad D = \frac{r(1+e)}{r-e}\left[\frac{(1+r)^n-(1+e)^n}{(1+r)^n-1}\right] \qquad (6)$$

unless e is equal to r, and in this case,

$$D = n\left(\frac{r(1+r)^n}{(1+r)^n-1}\right)$$

Application

The most difficult part of applying life cycle cost analysis to a real problem is determining the proper numbers to use for the different costs and for the interest rate. There are actually two different ways to handle the interest rate, and the proper way depends on how inflation is being treated. One way is to ignore inflation when calculating present values or annual costs. This is accomplished by projecting increases in annual costs only if they are expected to be greater than those caused by inflation. Such increases are due to "real" price increases and the annual costs are in "constant" dollars. In addition, the "real" interest rate must be used which is found by subtracting the expected inflation rate from the rate of interest that is actually used by banks to make loans. The interest rate used by banks is called the "nominal" interest rate.

The other way to handle the interest rate is to include inflation in the analysis. Since inflation really does occur, and since banks include inflation when setting interest rates, the cost numbers found when inflation is included are close to the amounts that are actually paid. In this case, the expected inflation rate must be included with the "real" price increases when projecting increases in annual costs. Also, the proper interest rate to use is the one that is available for private loans at banks, provided the inflation rate chosen is similar to the one assumed by lenders.

When applying life-cycle cost analysis to comparisons of solar with conventional heating and cooling, certain assumptions concerning costs can be made which simplify the analysis. This study uses those assumptions which are appropriate for residences. Different sets of assumptions apply to commercial buildings since they are usually equipped much differently than residences and because businesses usually finance their investments differently than home owners.

Assumptions In This Study

First, nominal interest rates are used rather than "real" rates so that the annual cost numbers that appear will be comparable to actual costs which would be paid by the consumer. An interest rate of 8 percent is used since home mortgages can be obtained at approximately this rate. It is assumed that the 8 percent figure is composed of 3 percent for the time value of money and risk and that the remaining 5 percent is to account for the expected rate of inflation. Thus, in the formulas for present value and annual costs, d is equal to r, r is equal to 0.08 and e is equal to 0.05 plus the fractional "real" increase in annual costs expected each year in the future. If a fractional decrease is expected, this number can be subtracted from 0.05.

The lifetimes of both the solar and conventional systems are assumed to be 20 years. One problem with this assumption is the treatment of the conventional auxiliary equipment used to back-up the solar equipment. If the lifetime of a conventional furnace without solar heating is about 20 years, then the same furnace used only as an auxiliary in a solar heating system should last somewhat longer. Thus, at the end of the 20 year period the auxiliary equipment has some salvage value. However, the present value of this salvage value at the beginning of the period is very small relative to the cost of solar equipment. Thus, it is assumed that neglecting this uncertain salvage value will not influence the outcome of the analysis. Also neglected is the cost for electricity to run the pumps or blowers on the solar system. This cost is negligible when compared with the cost of operating a heater or air conditioner.

Another assumption in this study involves the initial cost of the auxiliary equipment and the distribution system. Since a solar heating and cooling system requires auxiliary equipment which can supply 100 percent of the load during periods of inadequate sunshine, it is assumed that the initial cost of the auxiliary equipment and of the distribution system for the solar installation is the same as the initial cost of a conventional installation. This assumption is correct for most heating comparisons, but it is inaccurate for cooling comparisons. However, an adjustment, to be described later, can be made which validates the assumption for cooling.

The annual expenses for maintenance are also assumed to be the same for the solar and conventional systems. This assumption is not entirely accurate since the solar system involves additional equipment such as pumps and collectors. The collectors in particular may create special maintenance problems, since they are constantly exposed to the extremes of the weather. However, at this time little information is available on maintenance costs since only a few solar heating systems have been in operation for long periods of time. Thus, additional costs are not added to account for the possibility of extra maintenance expenses.

When a life-cycle analysis is performed using the assumptions described above, the comparison of solar versus conventional reduces to a comparison of the cost of the solar collector, the heat storage unit, and the auxiliary fuel with the cost of fuel for a conventional system. When this approach is taken, the solar collector and storage unit can be thought of as a replacement for fuel, and the cost of these two items can be called the solar "fuel" cost. Thus, the annual cost of solar "fuel" can be found by applying formula 6 to the initial collector and storage costs. This results in formula 7:

$$\begin{pmatrix}\text{ANNUAL SOLAR}\\ \text{"FUEL" COST}\end{pmatrix} = \begin{pmatrix}\text{INITIAL COST}\\ \text{OF COLLECTOR}\\ \text{AND STORAGE}\end{pmatrix} \times 0.102 \qquad [7]$$

since $\left(\dfrac{r(1+r)^n}{(1+r)^n-1}\right) = 0.102$ when r is equal to 0.08 and n is equal to 20.

The corresponding formula for auxiliary and conventional fuels is shown in formula 8 where D (of formula 6) is the adjustment for expected "real" and inflationary increases in conventional fuel prices:

When determining the annual cost of the auxiliary fuel, the "annual energy supplied" is that portion of the total yearly load which comes from the auxiliary equipment. When the annual cost of a totally conventional system is considered, the "annual energy supplied" is the entire yearly load.

Complications arise when combined heating and cooling comparisons are made since conventional heating equipment operates differently than conventional cooling equipment. In such cases, the annual auxiliary or conventional fuel cost must be found by adding the two cost numbers that are found by treating heating and cooling separately. For example, if the conventional alternative to solar energy is oil heating with electric air conditioning, the separate heating and cooling costs are computed using different costs per unit of energy, different amounts of annual energy supplied, different equipment efficiencies, and perhaps different fuel cost increase factors.

Another complication results when it is not true that the cost of solar auxiliary equipment is equal to the cost of conventional equipment. However, adjustments can be made to formulas 7 and 8 so that comparisons of "fuel" costs are still valid. An adjustment made in this study involves solar cooling equipment.

A solar cooling system requires an absorption type air conditioner which is more expensive than the electric air conditioners used in most air-conditioned homes. It is assumed in this study that an electric central air conditioner for a residence costs \$1000 in 1975. Thus, the cost of solar cooling is found by adding to the collector and storage costs the cost of an absorption air conditioner and subtracting \$1000. The resulting annual solar "fuel" cost can still be compared with the cost of conventional fuels.

Further complications arise when comparing a solar system using one type of auxiliary equipment with a conventional system of another type. An example is a solar heating system with electric resistance back-up equipment compared with an oil furnace. The adjustments required are

$$\begin{pmatrix}\text{ANNUAL CONVENTIONAL}\\ \text{FUEL COST}\end{pmatrix} = \left[\begin{pmatrix}\text{COST OF FUEL PER}\\ \text{UNIT OF ENERGY}\end{pmatrix} \times \begin{pmatrix}\text{ANNUAL}\\ \text{ENERGY}\\ \text{SUPPLIED}\end{pmatrix} \times D\right] \div \begin{pmatrix}\text{EQUIPMENT}\\ \text{EFFICIENCY}\end{pmatrix} \qquad [8]$$

dependent on the relative costs of the different equipment. This study assumes that comparisons are made between systems using the same type of conventional equipment.

Energy Costs

It was shown in formulas 7 and 8 that the amount of energy supplied by the solar equipment must be known before a uniform annual cost number can be found. It will be shown later in this chapter that by examining the variations in cost and performance that occur when various amounts of collector area are used, the system can be sized to provide energy to the building at minimum cost. A useful number for determining the proper size is the cost per unit of energy delivered to the building. This number is called the "energy cost", and it can be computed for both solar and conventional systems.

The energy cost of solar energy is found by dividing the annual solar "fuel" cost in formula 7 by the amount of energy supplied by the solar equipment each year. Since both the cost and the annual performance of solar equipment increase as the amount of collector area increases, the energy cost varies with the size of the system. The solar energy cost is found using formula 9.

The remaining sections of this chapter discuss solar costs and performance and show how a system can be optimally sized when the nature of variations in the energy cost is known.

The energy cost of conventional fuels is found by dividing the annual conventional fuel cost in formula 8 by the annual total amount of energy supplied by the conventional system. When combined heating and cooling is considered, the energy cost must be calculated by adding the cost of heating to the cost of cooling and dividing the sum by the total amount of energy used by both types of equipment during the year. This calculation is shown in formula 10 where the efficiency of air conditioning equipment is expressed as the "coefficient of performance".

Since the conventional heating and cooling energy cost depends on the relative amounts of energy required for heating and cooling, the level of the cost will change from year to year. If data for an average year is used to compute this cost, the same data must be used for the solar calculations. However, a simplification results when heating is compared alone. In this case, the energy for cooling is zero, and the energy for heating is equal to the total annual energy use. Thus, formula 10 reduces to formula 11 for heating comparisons.

$$\begin{pmatrix}\text{SOLAR}\\\text{ENERGY}\\\text{COSTS}\end{pmatrix} = \left[\begin{pmatrix}\text{INITIAL COST}\\\text{OF COLLECTOR}\\\text{AND STORAGE}\end{pmatrix} \times 0.102\right] \div \begin{pmatrix}\text{ANNUAL}\\\text{SOLAR ENERGY}\\\text{SUPPLIED}\end{pmatrix} \qquad [9]$$

$$\begin{aligned}\begin{pmatrix}\text{CONVENTIONAL}\\\text{HEATING \& COOLING}\\\text{ENERGY COST}\end{pmatrix} = {} & \left(\frac{\text{ENERGY FOR COOLING}}{\text{TOTAL ANNUAL ENERGY USE}}\right) \times \left[\left(\frac{\text{COST OF COOLING FUEL PER UNIT OF ENERGY}}{\text{COEFFICIENT OF PERFORMANCE}}\right) \times D\right] \\ & + \left(\frac{\text{ENERGY FOR HEATING}}{\text{TOTAL ANNUAL ENERGY USE}}\right) \times \left[\left(\frac{\text{COST OF HEATING FUEL PER UNIT OF ENERGY}}{\text{FURNANCE EFFICIENCY}}\right) \times D\right]\end{aligned} \qquad [10]$$

$$\begin{pmatrix}\text{CONVENTIAL}\\\text{HEATING ENERGY}\\\text{COST}\end{pmatrix} = \left[\begin{pmatrix}\text{COST OF HEATING}\\\text{FUEL PER UNIT}\\\text{OF ENERGY}\end{pmatrix} \times D\right] \div \begin{pmatrix}\text{FURNACE}\\\text{EFFICIENCY}\end{pmatrix} \qquad [11]$$

Components of Cost

The purchaser of a solar heating and cooling system today pays a price that is determined by four different types of cost: engineering cost, material cost, labor cost, and marketing cost. The material, labor, and marketing costs are each composed of two components: a constant cost component that does not vary with the size of the system, and a varying cost component that increases with the system size. The varying component consists of collector costs which generally vary linearly with the total collector area.

Communications with several companies presently producing solar components and installing solar heating systems, and with the managers of several solar demonstration projects in the United States have yielded data useful in estimating the magnitude of each cost component. Additional information is available in contractors' reports to the NSF-RANN-Phase Zero Feasibility Study on Solar Heating and Cooling of Buildings (1). The constituents of each cost component are discussed in this section. Then dollar values for each component are chosen from the cost data to serve as inputs to the cost comparisons. Cost figures are assembled for a system providing heating and cooling in a single family, detached residence. The variations in costs that occur between different cities are not considered.

Engineering Costs

Engineering costs, which include charges for installation drawings and field instruction, observation, and inspection, are usually paid to a firm of consulting engineers. The cost for the drawings can be considerable because they include design information based on an engineering analysis performed for the specific location and for the type of the structure. Field supervision requires visits by an engineer or technician at the job site throughout the construction period. As the number of solar installations throughout the country increases, engineering costs will decrease substantially or perhaps disappear. Increased knowledge of the system size requirements for various locations and standardization of design will enable the purchaser, his architect, and the building contractor to choose from among several different designs. At present, however, the consumer must obtain these services at a cost of about $1200.

Material Costs

Material costs are those paid by the equipment suppliers to obtain the materials from which the solar equipment is assembled. The *constant* component of this cost is composed of the costs of the pumps, tanks, heat exchangers, valves, pipelines, and fittings for a water system, or the costs of ductwork, louvers, pebble bed, and blowers for an air system. Actually, the required size and amount of most of this equipment does vary somewhat with the size of the system. But the amount of variation is highly dependent on characteristics of the specific installation (lengths of pipeline or ductwork, number of fittings, etc.), and this aspect can not be included in a general cost study.

The cost of the storage unit is also treated as constant in this analysis. The performance of a solar system is somewhat insensitive to the storage capacity for the range of system sizes normally required in the United States (16). Therefore, it is economical to size the storage unit on the basis of standardly available equipment.

The addition of cooling capacity to the system involves additional equipment that usually costs substantially more than a conventional electric air conditioning system. Since absorption air conditioners adapted for solar heat are not yet sold commercially, equipment built for natural gas firing is currently converted for use in solar cooled buildings. The cost attributable to the solar system is calculated by subtracting the cost of a conventional cooling system from the total cost of the solar cooling additions.

The dollar value for the constant material cost used in this study is based on the detailed cost accounting performed on the recently constructed Solar House I at Colorado State University where a water system was used (17). Table 2 contains a breakdown of costs by equipment type. The constant material cost of an air system is actually somewhat less (18).

The *variable* component of the material cost is the material cost of the collector. The cost of a flat plate collector built for either water or air as the distribution fluid is composed of costs for a

Table 2: Constant Material Costs (1975)

Item	Cost
Solar Heating	
Thermal Storage Tank	$250
Collector Pump	50
Collector/Storage Heat Exchanger	400
Domestic Water Preheat Tank	50
Automatic Bypass Valve	50
Associated Pipeline, Valves Fittings, etc	300
Control Instrumentation	200
Heating Constant Material Cost Total	$1300
Cooling Additions	
3-Ton Modified Absorption Cooling Unit	$2000
Cooling Tower	500
Cooling Tower Pump	50
Conventional Cooling Cost Adjustment	-1000
Cooling Constant Material Cost Total	$1550

Source, Colorado State University Solar House I (17)

collector plate with the energy absorbent surface coating, one or two glass cover plates, and insulation. The water type requires tubing on the surface of the collector plate and the air type requires ductwork behind the collector plate. The material costs for both types of collectors are about the same.

Collectors can be either assembled as they are installed at the job site or preassembled in modular form at a factory. The material cost of the latter is greater due to the extra sheet metal or wood used to make the enclosure. The marketing of modular collectors adds even more to the cost. However, the reduction of assembly costs due to factory mass production techniques might offset the additional material costs if high volume production occurs.

Table 3 shows the percentage of the collector material cost attributable to each major material component. The range of values for the total collector material costs found in the cost data is displayed on the line graph in Figure 5. The placement of a dot on the graph indicates that the point was obtained from proprietary information supplied by a private collector producer. The sources of other data points are indicated with special symbols. The material cost of modular collectors has been adjusted for comparison with collectors installed on site. A figure of $4.00 per square foot is chosen to represent this cost.

Table 3: Collector Material Cost Breakdown

Material	Percent of Collector Material Cost
Collector Plate	41%
Glass	20%
Insulation	5%
Backpan	15%
Miscellaneous Material	19%
Total	100%

Source Private Collector Manufacturer (see Appendix C)

Labor Costs

Labor costs for assembly of the collector and for installation of the collector, storage unit, and other equipment make up a substantial portion of the entire cost. Laborers are supplied by a heating and ventilating contractor when an air system is installed and by a plumbing contractor when a water system is installed. Laborers may include plumbers, sheet metal workers, electricians, and carpenters. Estimates of the constant component of the labor cost range from $500 for the water system at the Colorado State University solar house to $1200 for an air system installed by a private contractor. A $900 figure derived from estimates provided in the Westinghouse Corporation report represents a useable average (1).

The varying component of the labor cost consists of the collector assembly and installation costs. Assembly labor costs of three producers of modular collectors are displayed on the line graph in Figure 5. The approximate average of 75¢ per square foot is 16 percent of the total cost of materials and labor for collectors. It is a somewhat smaller portion of the actual selling price.

Collector installation costs are more substantial than the assembly costs. Modular collectors and those assembled on site are usually installed as rectangular panels of about 20 square feet. Each panel weighs about 120 pounds and requires either two men or a crane for installation. A private solar contractor estimates a figure of $1.25 per square foot for collector installation costs.

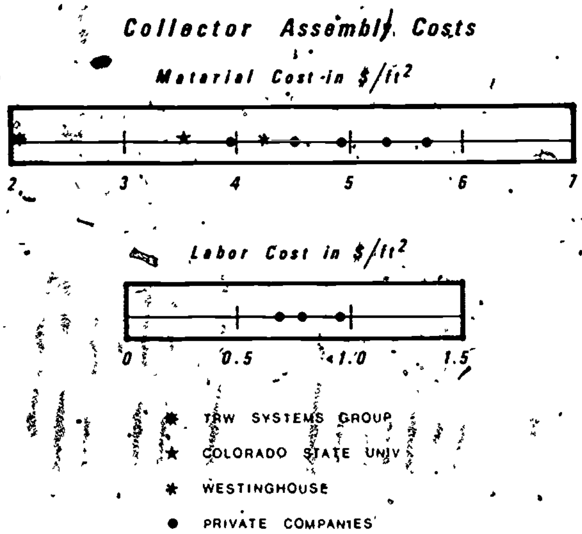


Figure 5. Display of collector assembly costs (See Appendix C for listing of private companies.)

When a collector assembly is installed on the roof of the building during building construction, collector installation displaces a portion of the roofing labor cost. On the other hand, if the collectors are installed on a separate structure as usually required for retrofit installations, additional material costs of about $2.00 per square foot are necessary for the structural support.

Marketing Costs

Marketing costs are the price mark-ups that occur at each link in the supply chain. In this analysis, the mark-ups on materials or components that are not unique to solar heating and cooling systems are included in the material cost. Solar marketing costs may be added by the collector factory, by the collector distributor, and by the solar system contractor. At each level, the marketing cost is composed of operating overhead, profit, inflationary contingency, and transportation costs.

Constant marketing costs are those which are added by the building contractor to all equipment except the collector. Currently, mark-ups of about 40 percent are being charged by solar contractors. However, this figure will decrease if continued solar industry growth induces competition among contractors. The marketing cost of the collectors is composed of a 10 percent mark-up at the factory and a 30 percent distribution mark-up. Since the contractor should be able to obtain collectors at factory prices, a composite 50 percent mark-up can be expected on the varying cost component when the contractor's mark-up is added.

At this point, there may be some confusion concerning what is meant by a mark-up of a certain percentage. The mark-up percentage is the percentage of the total price, including the mark-up, that is contributed by the mark-up. Solar costs are summarized in Table 4 and are displayed in a graph in Figure 6 for collector panel assembly areas up to 1000 square feet.

It should be recalled that only those costs associated with the collection and storage of solar energy are included in the solar cost accounting. The solar system equipment that is normally installed as part of a conventional system, such as the distribution system and auxiliary heating and cooling equipment, is not included. This is done so that the costs designated as "solar costs" can be compared with the operating fuel costs of conventional heating and cooling systems.

Potential Cost Reductions

The potential for reduction of solar equipment costs has been a topic of debate for several years. As previously mentioned, engineering costs are expected to decrease substantially over the next few years and collector assembly costs can be reduced with mass production techniques. Moreover, solar system assembly labor requirements may decrease with design improvements aimed at minimizing construction time.

Material costs will more likely increase than decrease, since material costs in all industries are on the rise. Only design innovations utilizing fewer and/or less expensive materials will lower material costs. The constant component of the material costs is almost independent of future mass production efforts since most of the equipment comprising this cost (pumps, valves, pipes, etc.) is already mass produced. Marketing costs will decrease proportionally with any material or labor cost decrease. Increasing competition may decrease the mark-up percentages by a small amount.

Table 4: 1975 Cost Summary

Type of Cost	Constant* Component ($)	Varying** Component ($/FT²)
Solar Heating		
Material	1300	4.00
Labor	900	2.00
Mark-up	1467	6.00
Engineering	1200	—
Total	4867	12.00
Cooling Additions		
Material	1550	—
Labor and Mark-up	1033	—
Total	2583	—
Heating & Cooling Totals	7450	12.00

* Does not vary with collector area
** Same as collector cost per square foot

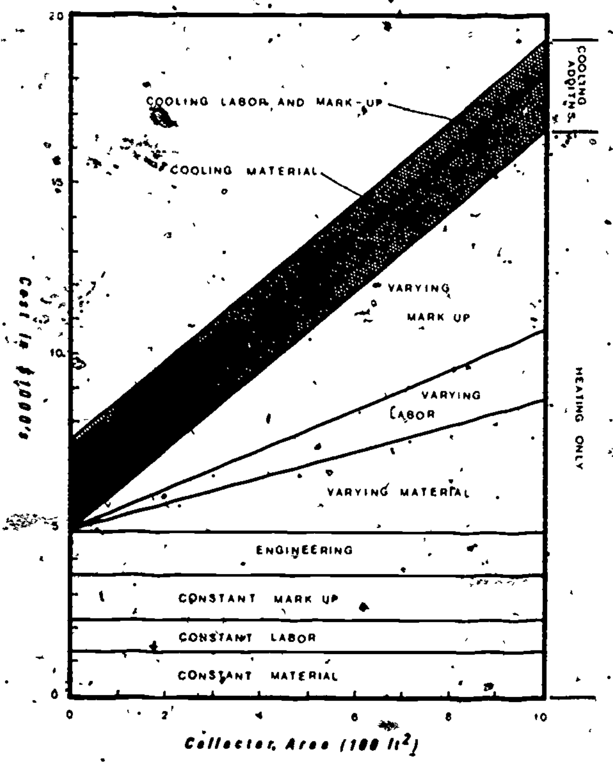

1975 Cost Summary*

Figure 6. 1975 costs in 1975 dollars for a residential solar heating and cooling system without mass production or advanced collector design.

Performance Characteristics

The economic feasibility of solar heating and cooling is highly dependent on the ability of the solar equipment to provide energy and on the amount of energy required each year to heat and cool the building. This dependency makes the economic evaluation highly specific to locations. Those areas of the country with characteristically high heating and/or cooling loads and plentiful amounts of sunshine are the best candidates for a solar installation. In such locations small systems can supply large load requirements. Areas with high thermal loads and small amounts of sunshine and areas with very low load are less likely to be economical sites.

For example, Miami is a poor location for solar space heating because the yearly heating demand is very low. It is, however, an excellent site for solar cooling and domestic water heating because of high insolation levels and high cooling requirements. The evaluation becomes complex in locations with more complicated weather characteristics. The weather conditions in most parts of the United States vary over a wide range during the year. Thus the performance evaluation of a solar space conditioning system is usually a difficult task requiring a large amount of data.

Performance Models

Mathematical models programmed on computers can accurately simulate the operation of solar heating and cooling systems at any location for which temperature and insolation data is available. Useful performance information is obtained in the form of a graph relating the amount of energy delivered to the load each year to the size of the collector. This information is obtained by simulating a year of operating time for several different system sizes.

Performance curves for various locations can be compared by dividing the solar energy delivered at each system size during a typical year by the total energy demanded during the year. The quotient is a number between zero and one representing the fraction of the load supplied by solar energy. This term is called the "solar fraction."

The performance models of greatest accuracy are those which use hourly weather data for an entire year. Equations based on the design characteristics of the system relate the hourly operation of the system to relevant parameters of the weather data. The data is chosen to represent a typical year at the location.

The accuracy of a model using hourly data is not required for the purpose of this study. Instead, a simpler less accurate model using average monthly data is used to obtain performance curves for solar space heating and hot water systems in 20 U.S. cities. This model, recently developed by Klein, Beckman, and Duffie at the University of Wisconsin, is based on the results of simulations that actually use data which is averaged each half hour for the heating period of an entire year (6).

The method uses a set of curves on a graph called an "f-chart" to determine the average solar fraction that can be expected during a one month period of operation. Monthly averages of solar radiation, temperature, and heating requirements are combined in the f-chart with collector absorptance, collector heat loss, and other system parameters. In this study the f-chart was adapted for use on a computer so that performance calculations could be made rapidly. Weather data was obtained from reference 20 and radiation data came from reference 19. The system parameters that were used are described below. A similar model for estimating the performance of combined heating and cooling systems is not yet available. Other solar heating models using monthly average data are described in references 21 and 22.

Performance Curves

Performance curves for a residential solar heating system in the city of Boston, Massachusetts are shown in Figure 7 for collector areas up to 1000 square feet. The residence is of average size with a floor area of 1500 square feet and a heat loss of 17,204 BTU per Fahrenheit degree day. Water is also heated for domestic use. Two curves are displayed. The lower curve is for typical flat plate collectors. The higher curve is obtained using advanced design collectors with

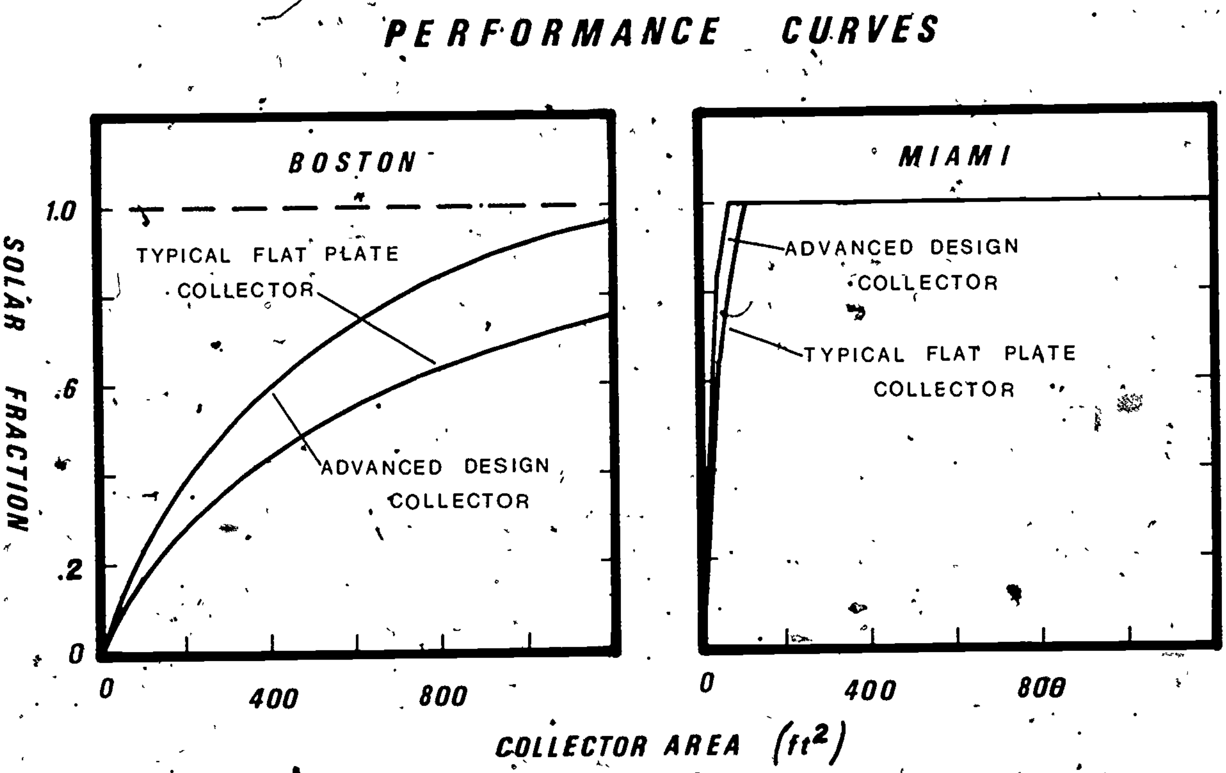


Figure 7. The range of solar heating performance variation in the U.S. is shown here. Solar Fraction is the fraction of the total annual heating load that is supplied by the solar equipment.

75 percent less heat loss and with an absorptive ability (glazing transmittance—plate absorption product) that is 15 percent greater. In terms of the parameters used in the model, the collector of average efficiency is described by a heat loss coefficient F_rU_l = 0.862 BTU/hr-°F-ft^2 and an energy absorption coefficient $F_r(\tau\alpha)$ = 0.72. The high efficiency collector is described by F_rU_l = 0.272 BTU/hr-°F-ft^2 and $F_r(\tau\alpha)$ = 0.83. These values of coefficients are currently achieved by evacuated glass-tube collectors with low lead glass for high radiation transmittance and a special collection surface for high absorption of incident radiation (7). Water is used as the heat transfer medium, and the storage unit contains 15 pounds of water (1.8 gallons) per square foot of collector area, providing storage for about 2 sunless days during the winter. The collector faces south and is tilted at an angle from the horizontal equal to Boston's latitude plus 15 degrees to obtain maximum winter heating performance (16). The performance of an air system with a similar amount of storage capacity is approximately the same.

In the range of small collector areas, performance is limited by the ability of the collector to absorb the required energy. Hence, performance increases rapidly with the size of the system. At large collector areas, performance is limited by the availability of sunlight, a large increase in collector area is required to obtain a small increase in performance.

The range of variation in performance across the United States is shown by including in Figure 7 a performance curve for Miami. In Boston, high heating loads and limited sunshine combine to create mediocre performance. A system with 1000 square feet of typical flat plate collectors supplies only 70 percent of the typical residential load. In Miami low heating loads and plentiful sunshine enable 125 square feet of collector to provide 100 percent of the heating needs in a typical year. Performance curves for the 20 cities analyzed in this study are included in Appendix A.

Cost Curves and Comparisons

An objective of great importance to the selection of a heating and cooling system is minimization of total cost. The cost of fuel for climate control with systems using conventional fuels is the fuel price adjusted by the conversion efficiency and by a factor accounting for future price increases. The selection of the system which minimizes fuel costs involves the simple comparison of the cost per BTU for each fuel. This cost is almost independent of system size.

The selection of the system characteristics is more difficult when solar energy is involved. The varying nature of solar system performance characteristics and the rapid increase of system costs with collector areas causes the cost of solar energy per BTU to vary with system size. The total annual cost of heating and/or cooling with solar equipment and auxiliary energy also varies with system size. The general nature of these variations is shown in Figure 8. The upper curve shows the solar "energy cost" in dollars per 10^6 BTU of heat delivered and the lower curve shows total yearly heating cost for the entire system. Two types of solar energy costs are involved: average and marginal. These cost curves are constructed by combining the results of the cost model and the performance model. The average cost curve is generated by dividing the annual cost for several different system sizes by the quantity of solar energy supplied with each different collector area. The marginal cost is the change in cost that is brought about by a small increase in collector area, divided by the corresponding increase in solar energy supplied to the home. The marginal cost curve is generated by finding the marginal cost at several different values of the solar fraction.

It is seen that minimum points occur on the cost curves. When the solar system is built to provide the capacity indicated by the minimum point on the average cost curve, solar energy will be delivered at the lowest possible unit cost. However, since this system size does not meet the total load requirements, conventional fuel must be used to supply the additional energy. The determination of the most economical size for the solar system is therefore dependent on the energy cost of the conventional fuel.

The adjusted cost of conventional fuels defines a horizontal line, rather than a curve, on the energy cost graph. If the average cost curve dips below this line, the total cost curve shows that the optimal system size (the size for minimum total cost) is found at the intersection of the increasing portion of the marginal cost curve

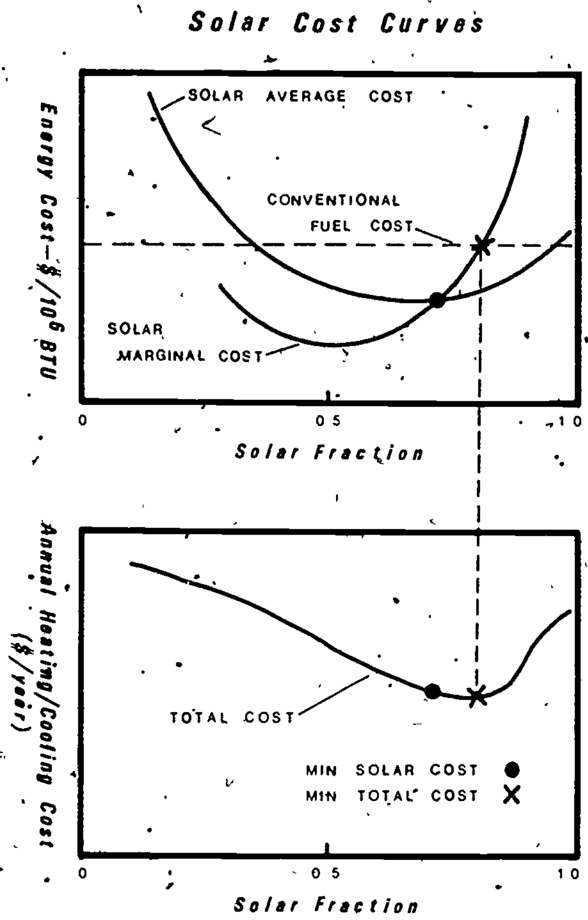


Figure 8. The general nature of cost variations with solar fraction is shown here. The upper graph displays separately the solar and conventional energy costs ($/10⁶ BTU). The lower graph shows the total annual cost ($/year) of the combined solar and auxiliary systems.

with the conventional fuel line. At this point the incremental costs of supplying energy by both means are equal, and increases in the portion supplied by either source results in higher total energy costs.

If the average cost curve does not dip below the conventional cost line, solar heating and cooling is not economical, in the normal sense, for the particular location. It is possible, though, that considerations other than price, such as conventional fuel scarcity and environmental preservation, may suggest to some persons that the "true cost" of the conventional fuel is somewhat greater than the price that exists on the market. These considerations are qualitatively treated in detail in the third chapter.

Figure 9 shows the average 1975 cost curves for solar heating (alone) in Rapid City, South Dakota and Boston, Massachusetts with the magnitude of the cost components displayed as a function of solar fraction. Costs per million BTU were computed for collector areas between 50 and 1000 square feet. Rapid City is a favorable location with plentiful sunshine and high heating load. Boston has a similarly high heating load, but poor performance due to low levels of winter insolation causes high costs per unit of solar energy. The minimum average cost in Rapid City is $10.50/10^6 BTU, whereas the minimum in Boston is $18.80/10^{6}BTU.

The level of the material cost indicates a low limit to cost reducing efforts with current designs. Figure 9 shows that at the minimum average cost point, material costs make up 31 percent of the total cost, with assembly and installation labor contributing 18 percent, marketing responsible for 40 percent, and engineering adding 11 percent. Reductions in engineering, marketing, and labor costs may occur due to mass production and widespread use. Design innovations might induce reductions in material costs. Chapter 3 presents cost analyses for each of the 20 U.S. cities using 1975 costs and costs derived from 2 cost reduction scenarios.

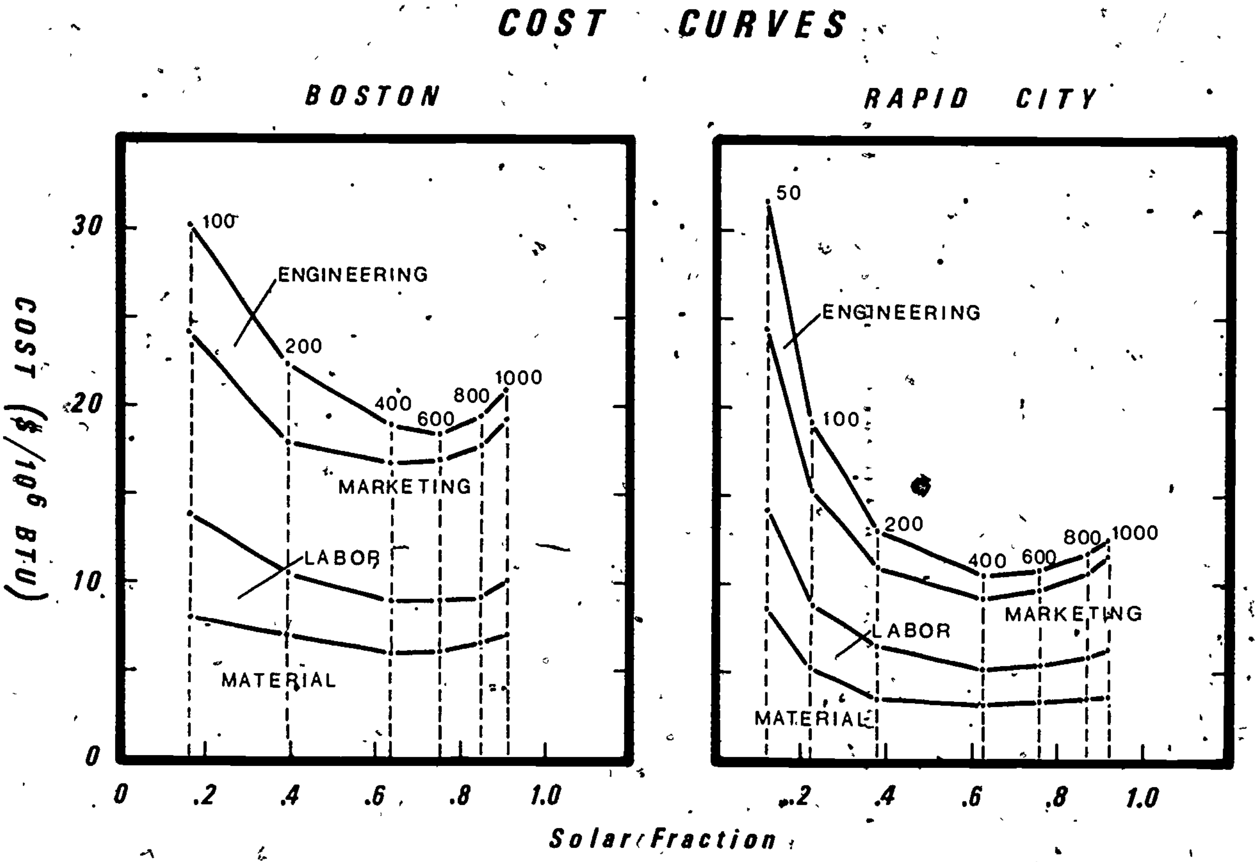


Figure 9. The relative importance of the different cost components in Boston and Rapid City is shown. The numbers on the top curves show the collector areas corresponding to the solar fractions.

CHAPTER 3

Solar Heating and Cooling in the United States

The method of economic analysis developed in the previous chapter is now applied to solar hot water and space heating in a new (not retrofitted) residence in various locations across the United States. The convenience of the University of Wisconsin solar heating performance model which requires only monthly average insolation and weather data enables the use of current and projected system cost and performance figures to perform economic analyses for several cities. Three sets of cost-performance numbers are used: costs and typical performance available in 1975, estimates of reduced costs achievable with mass production of flat plate collectors, and projected costs and performance achievable with mass production of an advanced collector design.

A convenient performance model is not currently available for solar cooling, due, in part, to the uncertainty about cooling unit performance. However, cooling performance is somewhat similar to heating performance since both depend on heat energy from the sun, and both are closely related to the energy demand (heating and cooling loads). Hence, some generalizations about cooling can be made from observations about heating performance. A hypothetical example based on the cost estimates for cooling equipment and on assumptions concerning cooling system performance shows how the addition of cooling equipment to create a combined heating and cooling system influences the economic comparisons.

Other important considerations are necessary for an assessment of solar heating and cooling in the United States to put the economic analysis in its proper perspective. These issues include the national security and environmental benefits from, and the institutional barriers to the development of solar heating and cooling in the United States. These issues involve considerations which both improve and question the potential for widespread solar development.

Economic Feasibility of Solar Heating: Twenty U.S. Cities

The selection of 20 cities for careful study of the economic feasibility of installing solar heating equipment on a detached residence is made on the basis of several considerations. First, all of the major geographic regions of the country are included. Large population centers are also included since great amounts of energy are used for climate control in urban areas. Several cities that are subjects of previous economic studies (most notably the eight city study of Lof and Tybout in references 10 and 16) are selected for comparison of past results with those from the present analysis. A final consideration is the availability of data for performance calculations. This study has relied on the insolation data for 80 cities assembled by Liu and Jordan and on temperature and degree-day data compiled by the Environmental Data Service of the National Oceanic and Atmospheric Administration (19, 20).

The reference building in all cases is a single family detached residence with 1500 square feet of floor area. The heating system characteristics are the same as those used to generate the performance curves in Chapter 2 for typical and advanced collectors. The collector is assumed to face south in each city with a tilt toward the vertical equal to the city's latitude plus 15 degrees.

Solar Cost Reduction Scenarios

Average cost curves have been generated for three cases covering the three sets of cost-performance figures. Case I describes the situation in 1975 with typical flat plate collectors, a total constant cost of $4867 and a total varying cost of $12 per square foot. Case II is the collector mass production scenario. Mass production of collectors using assembly line techniques is assumed to reduce assembly costs by 50 percent. Also a reduction of collector installation costs of 25 percent is used to indicate design improvements aimed at simplified installation. In addition, it is assumed that by the time mass production occurs the design of solar heating systems will have standardized to the extent that engineering costs are reduced to include only the cost of drawings for the particular installation. The mark-ups on the constant and varying costs are also reduced to indicate a competitive market for solar products. The components of the material, labor, and mark-up costs that do not vary with system size (constant components) are not reduced because the system components accounting for these costs are already being produced on a large scale for general use in the construction industry, and mass production of solar collectors will not affect their prices. Total constant costs for Case II are $3505, and total varying costs are $9.66 per square foot. One producer of air type solar heating systems expects to provide the installed system at prices near those of Case II in 1976 (18). The constant

Table 5: Cost-Components for the Three Cases

Constant ($)		Variable ($/FT²)	
CASE I:			
Material	1300	Material	4.00
Labor	900	Collector Assembly	0.75
	2200	Collector Installation	1.25
			6.00
40% Mark-up	1467		
Engineering	1200	50% Mark-up	6.00
Total Constant	4867	Total Variable	12.00
CASE II:			
Material	1300	Material	4.00
Labor	900	Collector Assembly	0.375
	2200	Collector Installation	0.94
35% Mark-up	1185		5.315
Engineering	120	45% Mark-up	4.345
Total Constant	3505	Total Variable	9.66
CASE III:			
Material	1300	Material	2.00
Labor	900	Collector Assembly	0.375
	2200	Collector Installation	0.94
35% Mark-up	1185		3.315
Engineering	120	45% Mark-up	2.215
Total Constant	3505	Total Variable	6.03

CASE I—1975 Costs with Typical Flat Plate Collector

CASE II—Mass Production Scenario

Conditions.
1) Engineering Reduced 90%
2) Collector Assembly Reduced by 50%
3) Collector Installation Reduced by 25%
4) Constant Mark-up Reduced to 35%
5) Variable Mark-up Reduced to 45%
6) Typical Flat Plate Collector

CASE III—Mass Production Plus Collector Improvements Scenario

Conditions.
1) All Case II Assumptions except 6)
2) Collector Material Costs Reduced by 50%
3) Advanced Design. High Efficiency Collector

material costs of an air system are usually somewhat lower than those of a water system.

Case III is a scenario assuming mass production of advanced, high efficiency collectors. Constant material, labor, and mark-up costs are again unchanged, and engineering and collector labor costs are the same as Case II leaving a constant cost total of $3505. Collector material costs are reduced 50 percent in this case to indicate design innovations which require fewer and/or cheaper materials than used for the typical flat-plate collectors. Collector efficiency is increased by using collectors with 75 percent less heat loss and 15 percent greater absorptive ability. The presumed collector cost is $6.03 per square foot. The assumptions and cost components for the three cases are summarized in Table 5.

Conventional Heating Costs

Data on the cost of heating with natural gas, oil, and electricity, has been collected from the suppliers of these fuels in each of the 20 cities. The data is presented in Appendix B. Oil prices and winter rate price schedules for natural gas and electricity current in September of 1975 have been used with assumed furnace efficiencies of 67 percent for gas, 62 percent for oil, and 100 percent for electric resistance heating. Electric heat pumps are not explicitly compared with solar heating. The efficiency of a heat pump is greater than 100 percent, and it can be greater than 200 percent in mild climates. However, the initial cost of a heat pump is greater than that of an electric resistance furnace. In general, the cost of heating with a heat pump is somewhat less than with electric resistance heating.

Whenever applicable, fuel cost adjustment charges in effect in late 1975 have been added to the basic rates. Also, the rate steps which lower the unit energy costs with increasing consumption have been used in the calculations. The costs of oil heating have been included only for those cities in eastern parts of the Nation where oil is used extensively for home heating.

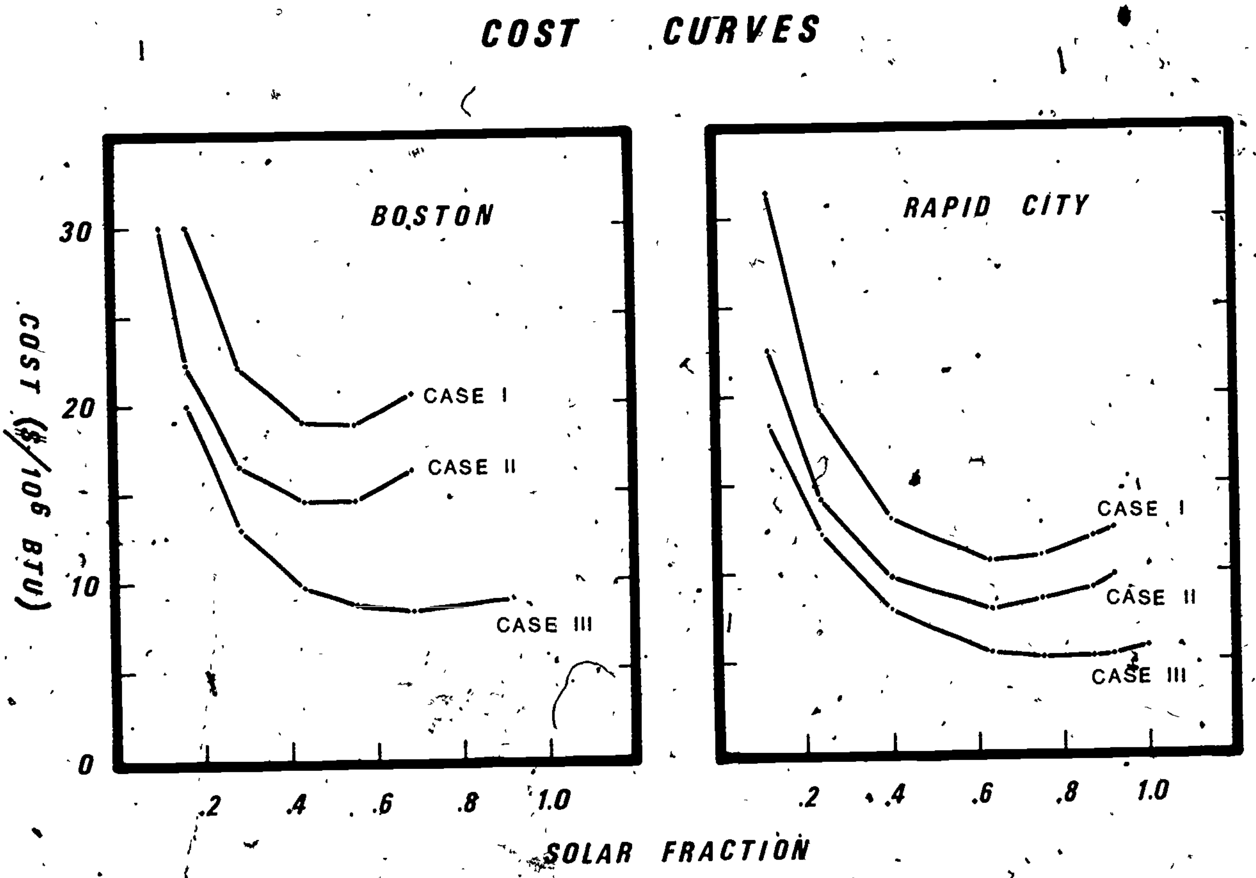


Figure 10. Solar heating cost curves. See Table V for Case I, II, and III assumptions.

Average Cost Feasibility Test

The average cost curves for the three cases are presented for each city in Appendix A. For example, the curves for Rapid City, South Dakota and Boston, Massachusetts are shown in Figure 10. The economic feasibility of a particular case is judged by whether the minimum point on the average cost curve dips below the lines (not plotted) which would be defined by the cost conventional fuels. Whenever this occurs solar heating is more economical than the fuels associated with the lines that are crossed.

Since the minimum point on the average cost curve is the determinant of economic feasibility, this point for each of the three cases in each city has been extracted for presentation and comparison with conventional fuels in Table 6. The minimum average solar energy cost is shown with the solar fraction obtained at minimum cost. Also shown are the energy costs of the alternative conventional fuels as computed by formula 11 in Chapter 2. Since a nominal 8 percent interest rate is used to compute solar costs, the conventional fuel costs are adjusted by a 5 percent inflation rate for the 20-year equipment lifetime. The adjustment factor D in formula 11 is computed on this basis. No increases in the "real" costs of fuels are assumed in computing the conventional heating energy costs.

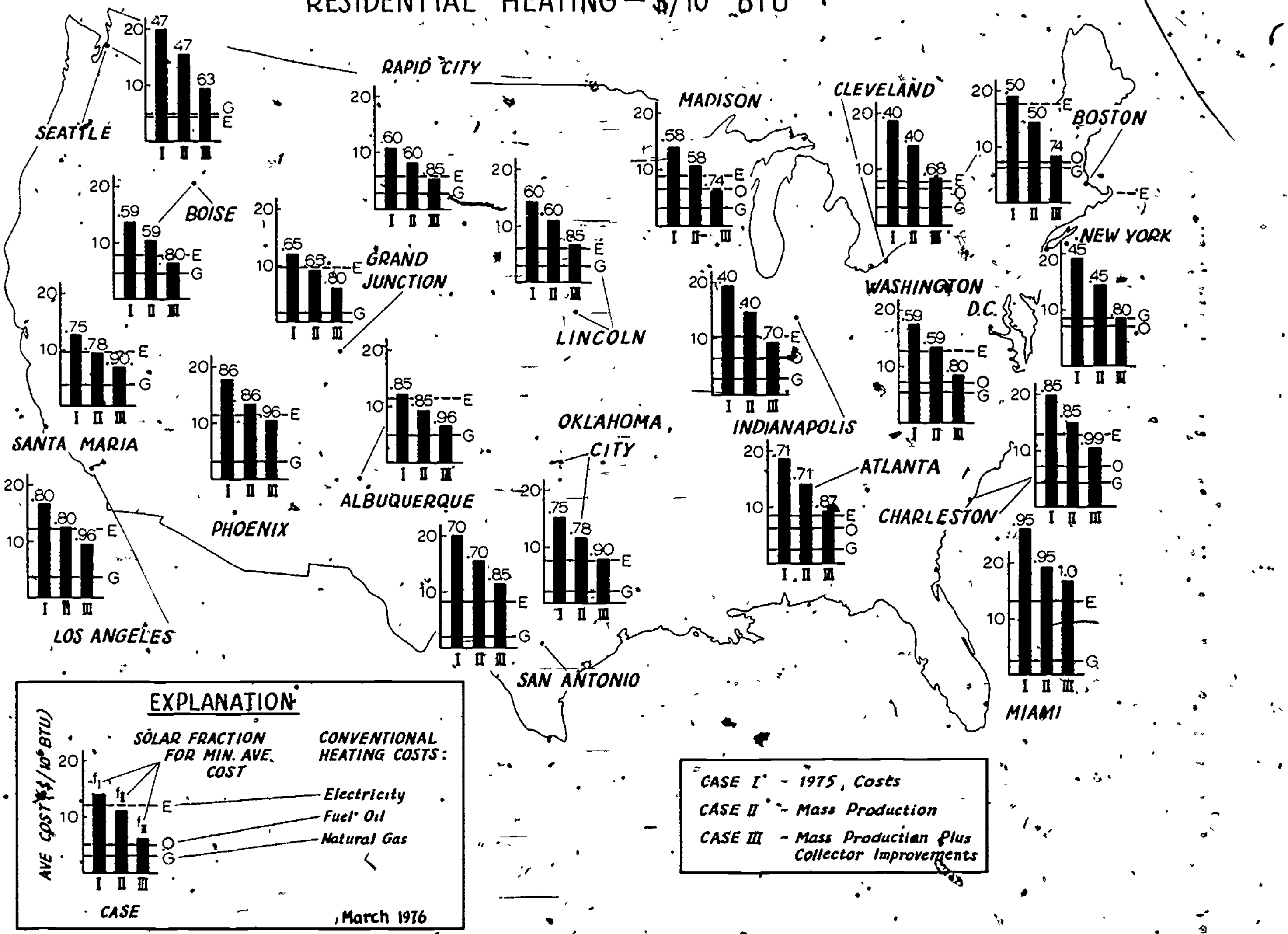
Figure 11 contains the information of Table 6 using bar graphs for each city placed near the location of the city on a map of the United States. The height of each bar indicates the level of the minimum average cost and the number above the bar indicates the value of the solar fraction at the minimum point. Conventional fuel costs are indicated by dashed lines drawn at the proper level to show cost in dollars per million BTU of heat. Whenever one of the three cases results in a bar with height less than some dashed line, solar heating is potentially less expensive than heating with the fuel associated with the dashed line. When that fuel is the only viable alternative to solar heating and when a solar heating system is installed, a savings will result over the lifetime of the equipment.

Table 6: Minimum Average Solar Energy Costs Compared With Conventional Fuels

		Adjusted Conventional Fuel Costs ($\$/10^6$ BTU)			Typical Performance			Advanced Design	
						$\$/10^6$ BTU			$\$/10^6$ BTU
	Yearly Heating Loads (10^6 BTU)	Elec.	Oil	Gas	Solar Fraction at Min. Av. Solar Cost	Case I	Case II	Solar Fraction at Min. Av. Solar Cost	Case III
Albuquerque, N.M.	97	11.4	—	4.9	0.85	12.2	9.3	0.96	6.5
Atlanta, Ga.	75	8.4	6.3	2.5	0.71	18.5	14.1	0.87	9.3
Boise, Idaho	122	7.7	—	4.5	0.59	13.7	10.5	0.80	6.6
Boston, Mass.	119	17.7	7.2	6.3	0.50	19.0	14.5	0.74	8.3
Charleston, S.C.	58	12.9	7.1	4.3	0.85	19.8	15.1	0.99	10.5
Cleveland, Ohio	126	7.8	6.6	3.2	0.40	18.7	14.3	0.68	8.4
Grand Junction, Colo	117	9.7	—	1.5	0.65	12.0	9.2	0.80	6.0
Indianapolis, Ind	117	10.3	6.4	2.8	0.40	19.4	14.8	0.70	9.2
Lincoln, Neb.	128	6.0	—	2.9	0.60	14.3	11.0	0.85	6.7
Los Angeles, Calif.	52	12.3	—	3.7	0.80	16.8	12.5	0.96	9.5
Madison, Wis.	154	8.8	6.4	3.2	0.58	13.9	10.7	0.74	6.3
Miami, Fla.	25	13.2	—	2.5	0.95	26.0	19.3	1.00	16.8
New York, N.Y.	106	30.7	7.1	8.4	0.45	19.3	14.5	0.80	8.6
Oklahoma City, Okla.	85	7.5	—	2.0	0.77	15.3	11.7	0.90	7.8
Phoenix, Ariz.	48	11.5	—	3.2	0.86	17.9	13.4	0.96	10.5
Rapid City, S.D.	147	5.8	—	2.8	0.60	10.8	8.2	0.85	5.3
San Antonio, Texas	48	8.3	—	2.0	0.70	20.0	15.6	0.85	11.4
Santa Maria, Calif.	74	9.7	—	3.7	0.77	12.8	9.6	0.90	7.0
Seattle, Wash.	103	4.5	—	4.9	0.47	20.0	15.5	0.63	9.4
Washington, D.C.	94	12.7	7.1	5.4	0.59	17.7	13.5	0.80	8.5

MINIMUM AVERAGE SOLAR ENERGY COSTS

RESIDENTIAL HEATING — $\$/10^6$ BTU



CASE I - 1975 Costs
CASE II - Mass Production
CASE III - Mass Production Plus Collector Improvements

Figure 11. The heights of the bars show the minimum point on the solar average cost curves. The horizontal dashed lines are conventional heating costs adjusted for inflation. Solar heating can be cheaper than a partial alternative when the bar is lower than the dashed line. When this occurs, the optimal solar fraction is somewhat greater than the solar fraction that yields the minimum average cost.

Table 7 shows the percentage composition of the minimum average cost for each case. It has been found that the composition varies only slightly across the range of cities. This breakdown of costs shows which cost components are responsible for most of the total cost, and it enables the reader to speculate further on the effects of changes in the values of these costs.

Table 7: Cost Components as Percentages of Average Cost

Case	Material	Labor	Marketing	Engineering
I	31%	18%	40%	11%
II	39%	19%	40%	2%
III	35%	24%	38%	3%

The greatest savings is achieved by sizing the system so that the marginal solar energy cost is equal to the alternative fuel energy cost. This size is found by constructing a marginal cost curve as described in Chapter 2. The solar fraction that is associated with the optimal system size can be used to estimate the total collector area, the total capital cost of the solar equipment, and the total annual heating cost. Note that the optimal size is strongly dependent on the assumption concerning future conventional fuel price increases. Moreover, whenever solar heating is economical, the optimal solar fraction will be somewhat greater than the solar fraction at minimum average solar cost.

Price Increases

Since no increases in the "real" costs of fuels are assumed in computing the conventional energy costs, the comparisons obtained from Table 6 and Figure 11 are only initial comparisons. The comparisons change when assumptions are made concerning "real" price increases or inflation rates that differ from the expected, long-term average inflation rate used to compute interest rates. For example, if the cost of electric resistance heating in Charleston is assumed to increase at a "real" rate (in excess of inflation) of 2 percent per year, the adjusted lifetime energy cost for electricity is $15.5/10^6$ BTU rather than the $12.9/10^6$ BTU figure obtained when no real increase is assumed. The minimum average Case II solar heating energy cost in Charleston is $15.1/10^6$ BTU. Thus, when a 2 percent real increase in Charleston's electricity price is assumed, solar heating is economical, whereas without the increase it is not economical.

Increases in the cost of solar equipment due to increasing material and labor costs do not enter into the comparisons above because after the solar equipment is purchased and installed, the owner is immune to the effects of any price increase. However, when comparisons are made for purchases that occur sometime in the future, these price changes are relevant. If the solar heating system in Charleston in the example above is to be purchased in 1978, the expected increase in Case II costs between 1975 and 1978 must be incorporated into the comparison. If the system is purchased in 1980, Case III costs may be more appropriate, and the expected price increase between 1975 and 1980 must be used. These cost adjustments for future purchases are necessary because Case II and Case III costs are based on 1975 material and labor costs. It should be noted, though, that valid comparisons of future purchases can be made without these adjustments if it is assumed that the costs of material and labor for solar equipment increase at the same rate as conventional fuel costs during the period between 1975 and the purchase data.

Table 8 shows the annual percentage "real" increases in the prices of conventional fuels that are necessary to make solar heating economically feasible. The percentage increases are calculated by first finding the constant annual rate of increase in the price of each conventional fuel that is necessary throughout the 20-year lifetime to make the conventional energy cost equal to the minimum average solar energy cost for both Case II and Case III. This number is the same as "e" in Chapter 2. The "real" rate, given in Table VIII is then found by substracting the 5 percent inflation rate from "e."

Note that Case II solar heating can be competitive with electricity in 5 out of 20 cities with no "real" increase and in 9 out of 20 cities with a 2 percent "real" increase. Case III solar heating can be competitive with electricity in 13 out of 20 cities with no "real" increase and in 17 out of 20 cities with a 2 percent "real" increase. In addition Case III solar heating will be competitive with oil heating in 1 out of 8 cities with no "real" increase and in 3 out of 8 cities with a 2 percent "real" increase.

Table 8 Conventional Fuel Annual "Real" Price Increases

Annual Percentage "Real" Increases in Fuel Prices Necessary For the Economic Feasibility of Case II and Case III Solar Heating ("feasible" indicates that no increase is necessary)

City	Case	Electricity (%)	Oil (%)	Gas (%)
Alburquerque, N M	II	feasible	—	6.5
	III	feasible	—	3.0
Atlanta, Ga.	II	5.3	8.1	16.6
	III	1.0	4.1	13.0
Boise, Idaho	II	2.8	—	8.6
	III	feasible	—	4.2
Boston, Mass	II	feasible	7.1	8.4
	III	feasible	1.6	2.9
Charleston, S C	II	1.7	7.7	12.3
	III	feasible	4.2	9.0
Cleveland, Ohio	II	6.2	7.8	14.3
	III	0.8	2.6	9.6
Grand Junction, Colo	II	feasible	—	17.0
	III	feasible	—	13.2
Indianapolis, Ind	II	3.8	8.4	16.0
	III	feasible	3.8	11.8
Lincoln, Neb	II	6.2	—	12.8
	III	1.2	—	8.4
Los Angeles, Calif	II	0.2	—	12.0
	III	feasible	—	9.5
Madison, Wisc	II	2.2	5.3	11.8
	III	feasible	feasible	6.8
Miami, Florida	II	4.0	—	19.3
	III	2.6	—	18.1
New York, N Y	II	feasible	7.3	5.6
	III	feasible	2.1	0.2
Oklahoma City, Okla	II	4.6	—	16.7
	III	0.4	—	13.2
Phoenix, Ariz	II	1.6	—	13.8
	III	feasible	—	7.9
Rapid City, S D	II	3.6	—	10.8
	III	feasible	—	6.6
San Antonio, Tex	II	6.5	—	19.2
	III	3.4	—	16.5
Santa Maria, Calif	II	feasible	—	9.6
	III	feasible	—	6.6
Seattle, Wash	II	12.2	—	11.3
	III	7.6	—	6.6
Washington, D C	II	0.6	6.6	9.2
	III	feasible	2.0	4.8

Examples of Optimally Sized Systems: Three Cities

Three cities, Indianapolis, Los Angeles, and Washington, D.C. are chosen for a closer examination of solar heating system characteristics and costs, and for economic comparisons with electric resistance heating in each city. Marginal cost curves have been constructed for Case II and Case III solar heating systems on a typical single family residence in each city. The Case II system is assumed to be purchased in 1977. Hence, all costs are inflated to reflect expected 1977 prices. The Case III system is assumed to be purchased in 1980 and costs are likewise inflated to reflect expected 1980 prices.

Two scenarios are treated. Scenario I assumes that there will be no "real" increase in the price of electricity during the 20-year lifetime of the solar equipment. Scenario II assumes that there will be a 2 percent annual "real" increase in the price of electricity during the 20-year period.

Whenever solar heating is economically feasible, the optimal solar fraction is found by locating on the marginal cost curve the point where marginal costs are equal to the adjusted heating energy cost of electricity. The installation of a solar heating and auxiliary system with the corresponding optimal collector size will provide heating to the home at a cost which is, on the average, lower than that possible with any other collector size. Wherever solar heating is not economically feasible, it is assumed in the exampled presented here that a system is built to supply the solar fraction which yields the minimum average cost. In these cases, a negative savings or an economic loss results if a solar heating system is built.

The results of calculations for the two scenarios in the three cities are shown in Table 9. Note that the occurrence of savings and losses corresponds exactly to the economic feasibility indicators for these three cities in Tables 6 and 8 and in Figure 11. Recall that the optimal solar fractions are average values. This means that for a Case III system in Los Angeles, a system with an average solar fraction of 1.0 provides, on the average, 52 million BTU per year. An auxiliary unit is still required because certain years will have heating loads greater than 52 million BTU. However, if a homeowner in Los Angeles is willing to tolerate a few uncomfortably cool days or risk the occurrence of several cloudy and cold days, some additional savings can be realized by installing little or no auxiliary equipment.

Under the most favorable conditions for solar heating treated here (Case III under Scenario II), substantial annual savings result when solar equipment is installed. However, under the least favorable conditions treated here (Case II under Scenario I) sizeable losses can occur. These losses can also be interpreted as being the subsidy that would be required to motivate a person to purchase a solar heated home under the conditions of Case II and Scenario I when electricity is the only available conventional fuel. A similar interpretation applies whenever it is found that under certain conditions solar heating is not economically feasible.

"Do It Yourself" Possibilities For Retrofits

Home owners in America often avoid much of the cost of home improvements by doing most of the labor themselves. If mass produced solar equipment is designed for retrofit installations and sold in kit form, substantial savings can be realized. Labor costs can be reduced to the cost of collector assembly. Moreover, much of the marketing expense is eliminated since a building contractor is not required.

For example, if Case III costs shown in Table 5 are reduced to $1300 for the constant material component and $4.00 per square foot for the variable component, a 600 square foot system costs $3700 whereas the cost of a commercially installed Case III system is $7123. In this case, "do it yourself" possibilities represent a potential cost reduction of as much as 48 percent.

Additional Considerations for Cooling

A solar cooling system requires almost all of the equipment in a solar heating system plus additional equipment for air conditioning. Thus, it is almost always desirable to design a cooling system to provide heating as well. It is appropriate, therefore, to consider the economic analysis of solar cooling as an extension of the analysis for heating.

Table 9: 3 City Comparison of Solar Heating With Electric Resistance Heating

	Case II System Purchased in 1977 (1977 Dollars)						Case III System Purchased in 1980 (1980 Dollars)					
Cities	Optimal Solar Fraction	Optimal Collector Size (FT²)	Solar Capital Cost[1] ($)	Uniform Annual Solar Cost[2] ($/Year)	Uniform Annual Elect. Cost[3] ($/Year)	Discounted Annual Savings[4] ($/Year)	Optimal Solar Fraction	Optimal Collector Size (FT²)	Solar Capital Cost[1] ($)	Uniform Annual Solar Cost[2] ($/Year)	Uniform Annual Elect. Cost[3] ($/Year)	Discounted Annual Savings[4] ($/Year)
1) Scenario I: 5% Annual Rate of Inflation, 0% Annual Rate of "Real" Electricity Rate Increases												
Indianapolis	0.45	434	8486	1596	1327	-269	0.67	600	9091	1434	1537	103
Los Angeles	0.82	198	5977	737	704	-33	1.0	240	6320	645	816	171
Washington, D.C	0.59	398	8103	1368	1321	-47	0.90	597	9068	1078	1529	451
2) Scenario II: 5% Annual Rate of Inflation, 2% Annual Rate of "Real" Electricity Rate Increases												
Indianapolis	0.45	434	8486	1779	1660	-119	0.73	752	10,261	1596	2034	438
Los Angeles	0.85	221	6218	766	881	115	1.0	240	6,320	645	1079	434
Washington, D C.	0.65	474	8912	1487	1652	165	0.97	800	10,630	1145	2024	879

[1] Includes material, labor, marketing, and engineering costs for solar collector and storage unit

[2] Uniform annual cost of solar collector and storage unit (annual solar "fuel" cost) plus the annual cost of auxiliary electric resistance heating based on a discount rate of 8% for a period of 20 years and adjusted for 5% annual inflation

[3] Uniform annual cost of electricity for electric resistance heating based on a discount rate of 8% for a period of 20 years and adjusted for 5% annual inflation

[4] Savings are associated with solar heating Negative savings indicate the subsidy necessary to make solar heating economically competitive with electricity

Electric Utility Load Factors

Solar cooling has a physical advantage over solar heating since the periods of time with the greatest cooling requirements (sunny summer days) are the periods with the greatest availability of solar radiation. Currently, in many southern locations, electric utility companies experience poor annual load factors (the ratio of the annual peak load to the annual average load) because great amounts of electricity are required for air conditioning for only a portion of each year. Thus, the large generating equipment that is built to supply this peak load is idle during much of the year. This situation presents serious economic problems for utility companies since large portions of their capital investment do not generate revenue during much of the year.

Extensive use of solar cooling on new home construction in such areas would reduce the growth in the electric peak load and thereby lessen the requirements for construction of additional generating units. The greatest contribution from solar cooling would occur on hot sunny days when the electricity demand due to conventional air conditioning is greatest. Thus, the peak is smoothed out by contributions from solar energy, and load factors are increased. A simple calculation shows that the construction of 5000 solar cooled homes each with a solar air conditioning unit providing three tons of refrigeration eliminates the need for about 50 megawatts of peak generating capacity at the local utility company.

It is important to note, though, that the individual building owner will have his own economic interests in mind when deciding whether or not to install solar cooling equipment. If solar cooling is more expensive than electric air conditioning, it is not likely that he will choose to lose money in order to help the local utility company solve its peaking problems. Thus, in areas where solar cooling is not economical for individual buildings, the peak smoothing advantages of solar cooling can be realized only through a subsidy to building owners. The utility companies might find it advantageous to contribute to such a subsidization plan if the cost of the contribution is less than the loss incurred from adding generating capacity.

An Example: Solar Heating and Cooling In Atlanta

Consider a combined solar heating and cooling system with 400 ft^2 of collector area on a home in Atlanta. The solar heating performance curve for Atlanta in Appendix A shows that a Case III solar heating system of this size can provide, on the average, 87 percent of the annual heating load of 75 million BTU. Table 8 shows that solar heating is not economically feasible in Atlanta when compared with electric resistance heating unless the "real" price of electricity increases at an annual rate of at least one percent.

An owner of a home in Atlanta who desires both heating and air conditioning in his home might wonder how the addition of cooling equipment to a 400 ft^2 solar system will affect the economic feasibility. The results of an economic feasibility study are dependent on assumptions concerning the cost of solar cooling equipment, the performance of the equipment, and the cost of alternative air conditioning systems. The following example for Atlanta assumes values for solar cooling performance criteria and for the cost of electric air conditioning. Economic feasibility is then expressed in terms of the greatest amount that the additional equipment for solar cooling may cost for solar cooling to be as cheap as electric air conditioning.

Assumptions and Calculations

Performance Assumptions: 400 ft^2 of high efficiency collector (Case III) area and a three ton absorption air conditioner is assumed to provide, on the average, 50 percent of the annual cooling load. It is also assumed that with a three ton air conditioner having a coefficient of performance of 2.3, 1200 hours of operation are required each year in Atlanta to maintain a comfortable indoor temperature.

Electricity Price Assumptions: Two electricity price increase scenarios are hypothesized which are the same as those used in the solar heating examples in Table IX. *Scenario I:* Five percent annual rate of inflation, zero percent annual rate of "real" electricity rate increases. *Scenario II:* Five percent annual rate of inflation, two percent annual rate of "real" electricity rate increases.

Other Assumptions: The system is to be purchased in 1980. The cost of purchasing and installing the alternative three ton electric air conditioner is $1000 in 1975. Also, electric resistance heating is used, so that the home is "all electric."

The unform annual costs of both the electric and solar systems is found using formula 6 in Chapter 2. The annualized initial expense of the equipment for an electric air conditioner in 1980 is found to be $130 per year assuming annual inflation of 5 percent and an interest rate of 8 percent. The uniform annual operating expense of the electric air conditioner is found to be, in 1980 dollars, $202 per year under Scenario I and $267 per year under Scenario II. Similarly, the uniform annual operating expense of the electric resistance heater is found to be, in 1980 dollars, $808 per year under Scenario I and $1070 per year under Scenario II.

Formula 12 which follows directly from Formula 6 is used to determine the capital cost of solar cooling equipment which equates the uniform annual cost of solar heating and cooling with the uniform annual cost of electric heating and cooling.

$$\begin{pmatrix}\text{Maximum}\\ \text{Feasible}\\ \text{Cost of}\\ \text{Solar Cooling}\\ \text{Equipment}\end{pmatrix} = \left\{ \left[\begin{pmatrix}\text{Uniform Annual}\\ \text{Cost of Electric}\\ \text{Heating and}\\ \text{Air Conditioning}\end{pmatrix} - \begin{pmatrix}\text{Uniform}\\ \text{Annual}\\ \text{Cost of}\\ \text{Solar}\\ \text{Auxiliary}\\ \text{Fuel}\end{pmatrix} \right] \div \begin{pmatrix}\text{Capital}\\ \text{Recovery}\\ \text{Factor}\\ (0.102)\end{pmatrix} \right\} - \begin{pmatrix}\text{Capital}\\ \text{Cost of}\\ \text{Solar}\\ \text{Heating}\\ \text{System}\end{pmatrix} \qquad [12]$$

The capital cost of a solar heating system purchased in 1980 under Case III assumptions is $7552. The uniform annual cost of auxiliary electricity for both heating and cooling is $206 per year under Scenario I and $273 per year under Scenario II, both in 1980 dollars.

With the assumptions laid out above, Formula 12 is used to determine that the maximum feasible cost of purchasing and installing solar cooling equipment in 1980 is $1605 under Scenario I and $4154 under Scenario II. In 1975 dollars, these costs are equivalent to $1258 under Scenario I and $3255 under Scenario II. The estimate in Chapter 2 of the actual cost of adding solar equipment in 1975 is $3583. Thus, under the assumptions presented here, a combination of lower solar cooling equipment costs and higher electricity prices is necessary for solar cooling to become economically feasible in Atlanta. A more detailed and accurate assessment of the economic feasibility of combined solar heating and cooling requires an accurate performance model for solar cooling and better estimates of the purchasing and installation costs of solar cooling equipment.

National Security, Environmental, and Institutional Considerations: The Role of the Public Sector

The feasibility and desirability of using solar energy for heating and cooling a building is dependent on other factors besides technical and economic contingencies. Several considerations exist which may influence a building owner to act in a manner which is not normally cost effective when choosing a climate control system. Also, the institutional arrangements that exist in the locality of the building may act to encourage or inhibit the installation of solar equipment. The actions of the public sector of the economy, comprised of the Federal, State, and local governments, must be considered since their effects on economic conditions can be considerable. These issues are summarized here to show that a strictly economic assessment is inadequate to judge the feasibility or potential for utilizing solar energy.

When a building is heated or cooled with a properly designed solar system, the occupants can be fairly sure that a fraction of the total load approximately equal to the solar fraction will be delivered by the solar equipment during most years. Also, once the solar system is purchased and installed, the cost of the solar energy does not increase. Until recent years, conventional fuels such as oil, natural gas, and electricity have also been reliable sources of energy with fairly stable prices. Recently, though, crises conditions have caused all fuel prices to increase considerably. In addition, fuel oil has required rationing, natural gas suppliers have curtailed supplies to many cities, and electric utilities have experienced "brown-outs." The occupants of buildings utilizing solar energy for most of the heating or cooling supply are protected from shortages and price increases which threaten the comfort of occupants of buildings utilizing conventional fuels. Fuel price and supply fluctuations effect only that portion of the load carried by the auxiliary system.

The measure of security obtained by occupants of solar heated and cooled buildings will be translated into increased national security if solar equipment is installed on a large portion of the Nation's buildings. The scenarios for solar development and growth presented in Chapter I show that if high levels of growth occur, solar energy can supply a quantity of energy equivalent to several million barrels of oil per day. This quantity of energy would be supplied from a secure source that is not subject to depletion or embargo.

The conversion of solar energy into energy for heating and cooling is a process which is essentially pollution free. If solar equipment replaces a large portion of the heating and cooling load currently supplied by conventional fuels, air pollution problems will be reduced in areas where oil furnaces are prevalent. In addition, heating and air conditioning will be less responsible for the pollution problems caused by electric power generation.

When comparing the cost of solar heating and cooling with conventional heating and cooling on a dollar per unit of energy basis, the security and environmental benefits of solar energy can be accounted by adding to the conventional fuel cost an additional cost reflecting the cost of insecure fuel supply and environmental pollution. The addition of this extra cost will improve the cost comparison in favor of solar energy by increasing the optimal solar fraction if solar is already economical or by raising the conventional fuel line to a level which is closer to the minimum point on the solar cost curve if it is not economical.

It should be noted, though, that the owner of a single building has little incentive to consider national security or environmental protection when deciding whether or not to install solar equipment. He will, however, value the comfort and economic security of the building's occupants so he may include the cost of an insecure conventional fuel supply when considering which type of system to use. National security and environmental preservation are the responsibility of the public sector. The Federal and State governments can take advantage of the national security and environmental benefits of solar energy by encouraging the building owner to install solar equipment. This can be done by forcing the building owner to account for the true cost of conventional fuels through upward price regulation of these fuels and/or by subsidizing the purchase of the equipment. This subsidy can occur in the form of a low interest loan, a tax deduction, or a grant.

Governments can also help to lower solar costs by investing money in solar research, development, and demonstration. Cases II and III of the cost curves show the improvements in economic feasibility possible with mass production and collector improvements. The Federal Energy Research and Development Administration (ERDA) has developed plans to support a large number of demonstration projects requiring much equipment which may stimulate private producers to develop mass production techniques. Research is also supported for the development of high efficiency collectors which may result in the production of an improved, lower cost collector (23,24).

This discussion of public sector involvement has focused on the initiation of new government programs that will encourage the use of solar energy. However, existing arrangements in governments and other institutions often present barriers to the use of the sun's energy. Legal codes and institutions in this Nation have built up around an energy supply system based on the use of highly concentrated forms of energy such as petroleum and natural gas. Distribution of this energy to residential and commercial buildings is accomplished by using pipelines or wire cables which can be flexibly routed to connect almost any building to the energy source. When this concentrated energy is used for low temperature heating and cooling purposes, it is converted to a lower grade of energy in the form of heat.

Solar energy, on the other hand, is distributed naturally in the form of low grade heat energy. Concentration of solar energy for use in the more conventional ways is accomplished only by using elaborate focusing apparatus. Direct use of naturally distributed solar energy presents legal and institutional problems that are not encountered in the use of conventional fuels. Several studies have been and are being conducted through the support of the National Science Foundation, ERDA, and other agencies to assess the nature of these problems and to suggest solutions. Some of the problems are due to the nature of the energy form, such as the requirement for unobstructed air space above the collector and the capital intensity of the installation. Other problems exist because the concept is new to most people, and new arrangements are required within city governments, the building construction industry, and the companies that supply auxiliary fuels.

It is imperative that the collectors for solar installations in the United States have an unobstructed view of the southern sky. This requirement eliminates many locations as sites for solar buildings because of natural or man-made structures that block the sunlight. This problem can be encountered in mountainous regions and in cities where highrise structures are numerous. Sometimes special structures can be used to locate the collectors away from shadows, but the expense involved may be considerable.

Even if a location has easy access to sunlight, a potential problem exists if adjacent property is owned by another person. Under existing legal arrangements, the owner of the adjacent property has the freedom to plant trees and build structures without regard for the sunlight that will be blocked. Widespread use of solar energy would require that laws be set down establishing the right of a property owner to receive sunlight on his property. Existing zoning laws concerning the height of structures need to be modified to limit the construction of structures which block sunlight and to allow the construction of structures which enable access to sunlight (4).

Property taxes can create another barrier to widespread solar energy use (4). The addition of several thousand dollars worth of solar equipment to a building increases the value of the building for tax assessment purposes. Such a tax adds to both the constant and varying cost components of the solar equipment. These cost additions in turn raise the average cost per unit of energy, adversely affecting the comparison with conventional fuels. Modification of tax laws to exempt solar equipment from property tax assessment would eliminate this impediment. Tax laws can be further modified to encourage solar installations by reducing the taxes paid by owners of solar heated and/or cooled buildings. Such incentives can be conveyed through Federal and State taxes such as income and sales taxes as well as through local property taxes. An existing law which can improve the economics of solar heating and cooling involves deducting from income taxes the interest paid on the loan used to purchase the equipment.

Another problem resulting from the large capital requirement and also from the newness of solar energy is the reluctance of financial institutions to provide purchasing money at low interest rates and long amortization periods. The annualized costs for the average cost curves for residential solar heating were generated using an interest rate of 8 percent and an amortization period of 20 years. This type of loan can be obtained in 1975 for the purchase of a home. If the bank can be convinced of the reliability and fuel saving potential of solar heating and cooling systems, the same rates should apply to the solar equipment. If, however, the banker insists on a 10-year amortization period, the average cost per million BTU is increased by 46 percent. On the other hand, loan terms can provide another avenue for public sector involvement in the encouragement of solar development through a mechanism which has been used extensively: the government guaranteed low interest loan. If the interest on the 20-year loan used in the three scenarios is reduced from 8 percent to 4 percent through enactment of a Federal or State program, the average cost per million BTU is reduced by 28 percent. This savings actually represents a transfer of income from the general public to those who choose to make use of solar energy.

Another institutional problem involves the labor requirements for the installation of solar equipment (4). The division of tasks among the different groups of laborers involved in building construction is well defined for conventionally heated and cooled buildings. Agreements exist among the various construction labor unions concerning which types of laborers (carpenters, sheet metal workers, plumbers, roofers, etc.) should perform each task. It is uncertain, though, which type of workers should perform the tasks involved in assembling a solar heating and cooling system. For example, conflicts may arise between the roofers' and plumbers' unions over the responsibility for installing water-type collectors that replace the roof/structure of a home. Work sharing rules must be worked out through agreements between labor unions, or, if necessary, through State and Federal labor relations legislation before widespread construction of solar installations can occur. If agreements are reached at an early date, training programs on solar construction practices can be started within the unions to facilitate the transition from conventional fuels to solar energy for heating and cooling.

Suppliers of conventional fuels, such as natural gas distributors and electric power utility companies, may be adversely affected by concentrated development of solar heating and cooling in their service areas. Utilization of solar energy can potentially reduce the load growth of these suppliers if solar equipment is installed on newly constructed buildings. However, a reduced rate of load growth is desirable for some suppliers, such as gas companies faced with curtailed supplies and utility companies with overtaxed generating facilities.

On the other hand, if a solar installation is built to depend on these same suppliers for the source of auxiliary energy, load factor problems resulting from high peak loads might be exacerbated rather than alleviated. For example, if a large number of buildings in an area recieved most of their heating energy from the sun, the average load of the local natural gas supplier would be much lower than the load that would exist if all the buildings used natural gas. However, if all of these buildings depend on natural gas for auxiliary energy, a long period of sunless days would require a peak level of gas supply much larger than the average supply. This requirement might exceed the ability of the gas supplier to provide gas at a sufficient pressure. The problem can be more acute for an electric utility when electric heating is used extensively as a solar auxiliary fuel. This burden placed on fuel suppliers might motivate them to charge excessive rates to customers using their energy source as a solar auxiliary in order to receive an appropriate return on the investment required for transmission and generation facilities. Thus, the helpful effects of solar cooling on peaking problems might be offset by the problem of supplying auxiliary energy to solar heating systems.

One solution to the peaking problem might be the use of peak pricing to encourage solar equipment owners to charge their storage units during hours that the energy demand from conventional loads is low. Another solution is providing a tank at the solar installation for storage of a petroleum fuel to be used for auxiliary energy on a continuous basis or during periods that create peaking problems for electricity and natural gas suppliers.

In order to place the economic assessment of solar heating and cooling in its proper perspective, this section has discussed the range of other considerations that are necessary to judge its feasibility and desirability. These considerations involve and depend on the actions of Federal, State, and local governments and institutions. National security and environmental preservation considerations may justify the involvement of the government in creating new programs and modifying institutional arrangements to encourage the development and utilization of solar energy. The proper degree of involvement is dependent on the attractiveness of other new forms of energy utilization which also provide benefits to the public when replacing depletable and polluting energy sources.

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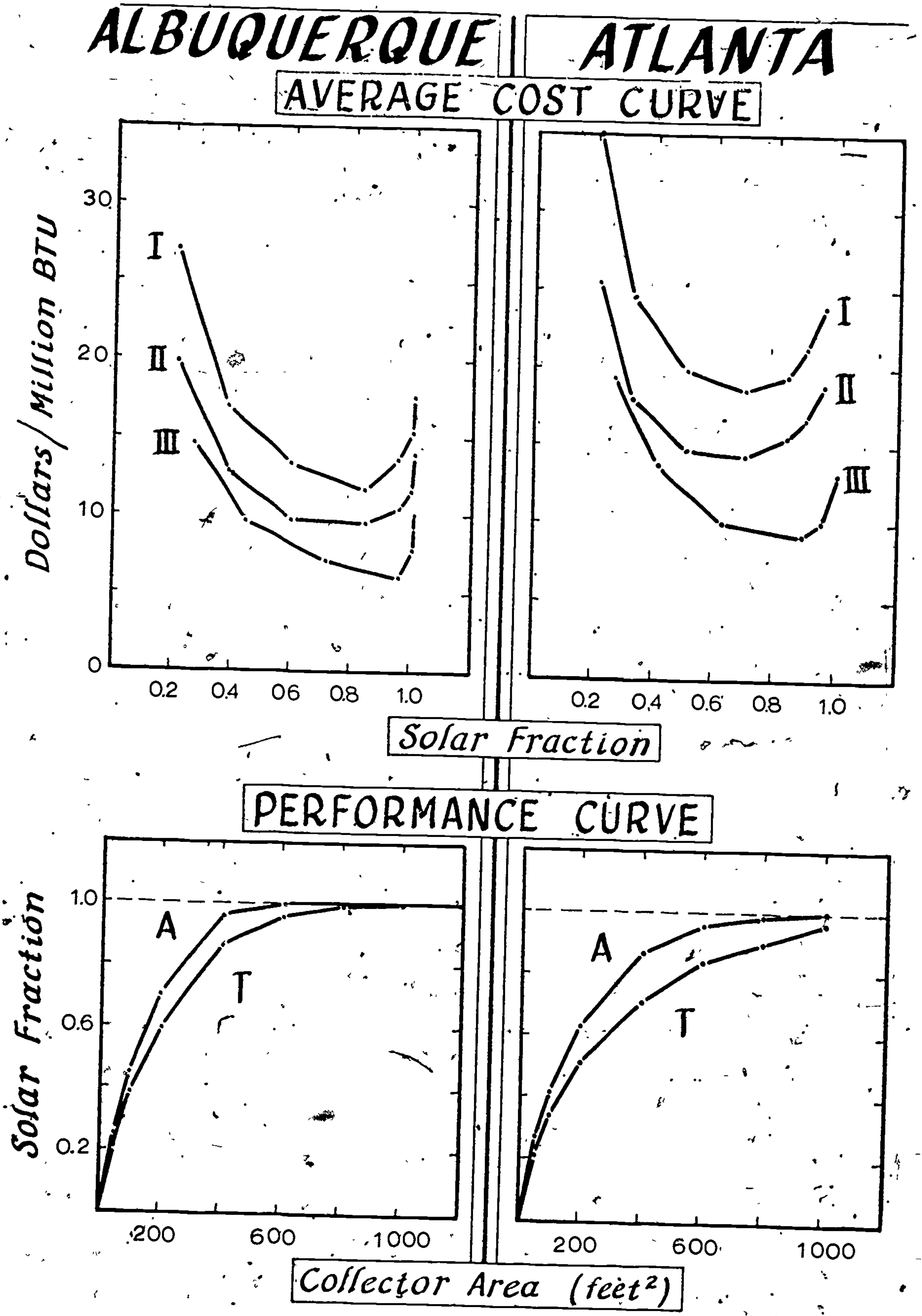
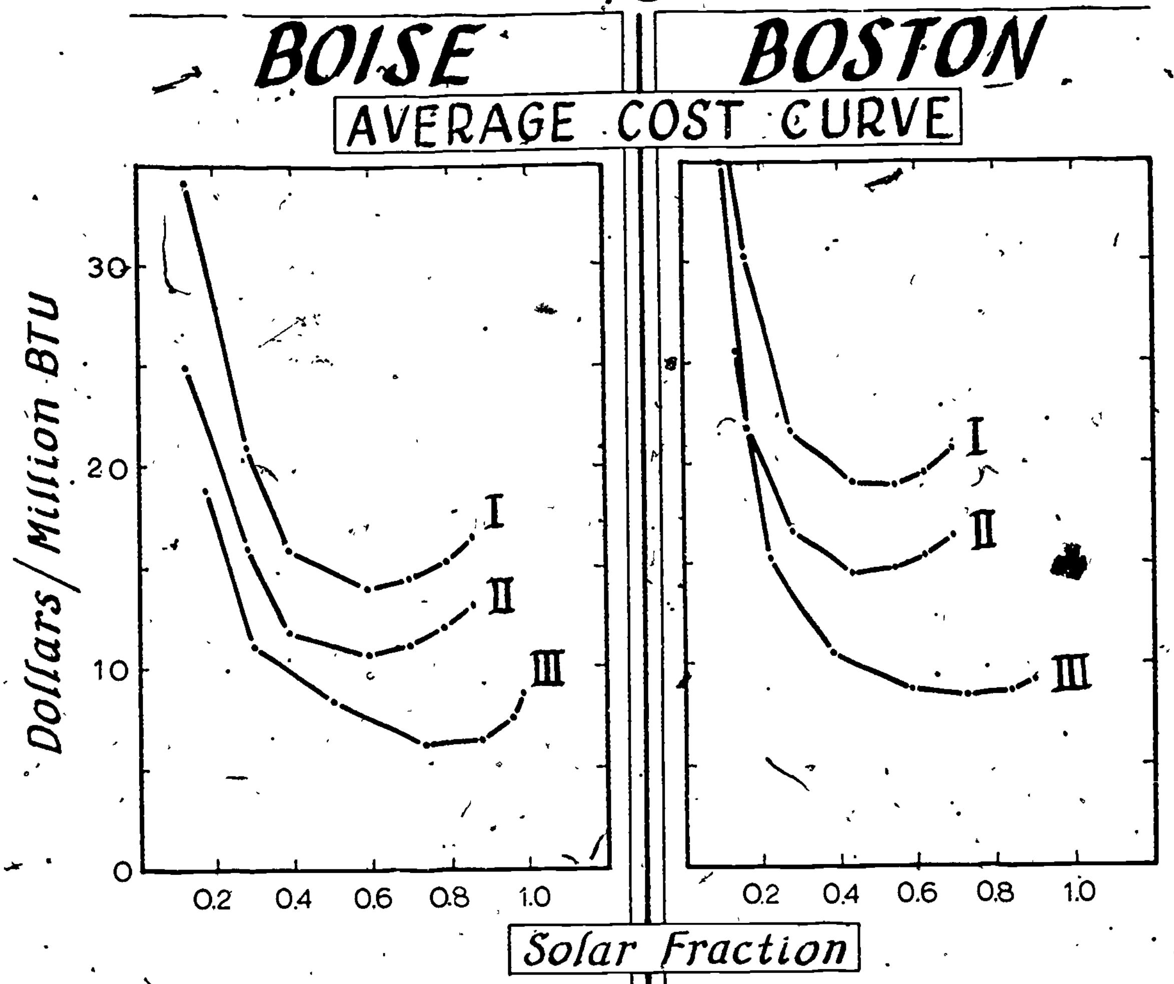
APPENDIX A

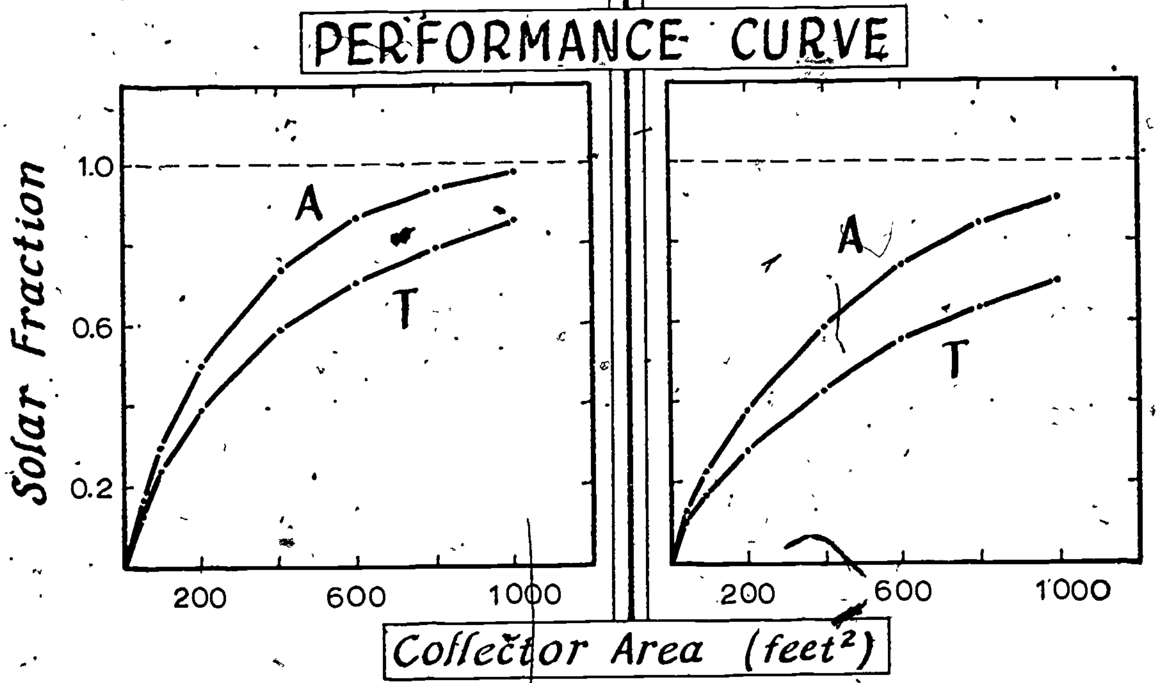
Cost and Performance Curves for Twenty Cities

Solar Energy Cost Curves for Cases I, II, and III Plus Solar Performance Curves for Typical Flat Plate and Advanced Design Collectors

Note: The Performance curves for typical flat plate collectors are denoted by "T". The performance curves for advanced design collectors are denoted by "A".

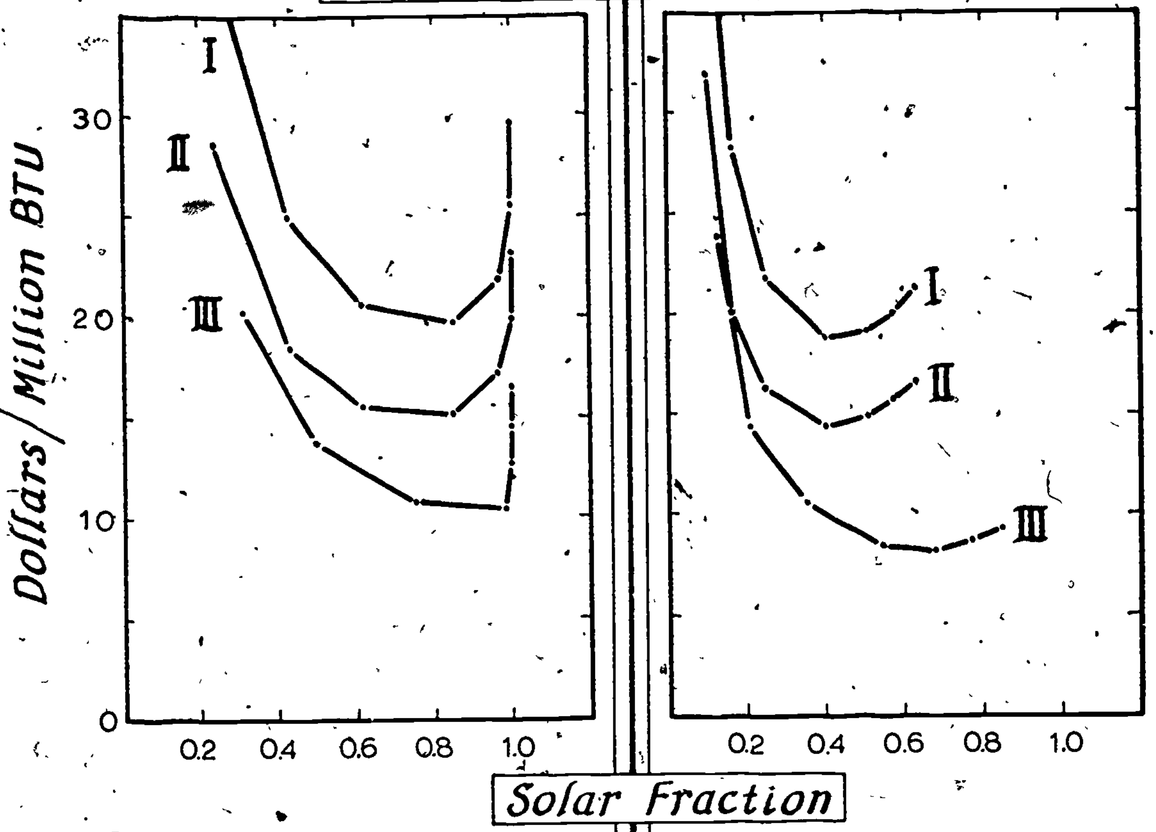

ALBUQUERQUE
ATLANTA
AVERAGE COST CURVE
Dollars/Million BTU
30
20
10
0
I
II
III
I
II
III
0.2
0.4
0.6
0.8
1.0
0.2
0.4
0.6
0.8
1.0
Solar Fraction
PERFORMANCE CURVE
Solar Fraction
1.0
0.6
0.2
A
T
A
T
200
600
1000
200
600
1000
Collector Area (feet²)


BOISE
BOSTON
AVERAGE COST CURVE
Dollars/Million BTU
0
10
20
30
I
II
III
0.2
0.4
0.6
0.8
1.0
Solar Fraction


PERFORMANCE CURVE
Solar Fraction
0.2
0.6
1.0
A
T
200
600
1000
Collector Area (feet²)

CHARLESTON | CLEVELAND

AVERAGE COST CURVE



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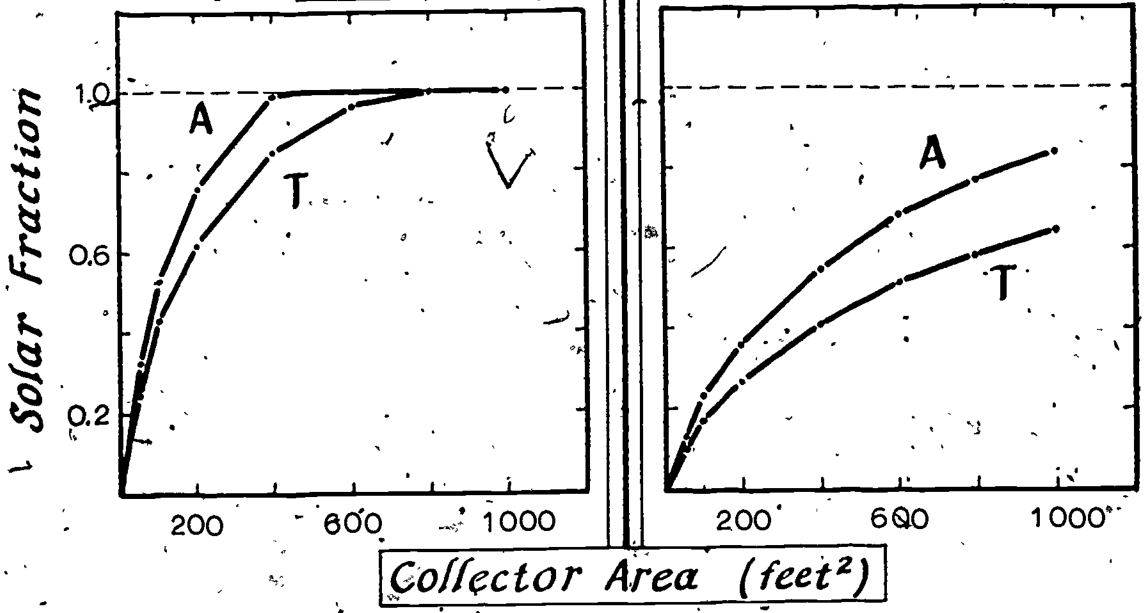
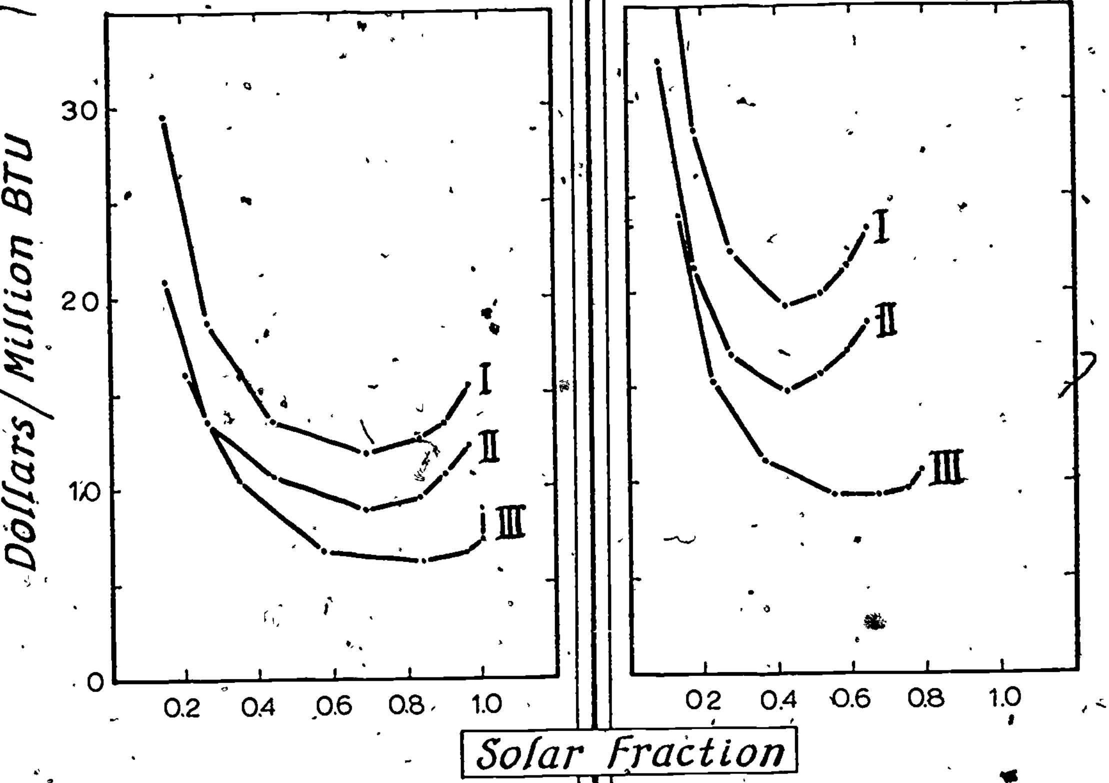


GRAND JUNCTION | INDIANAPOLIS

AVERAGE COST CURVE



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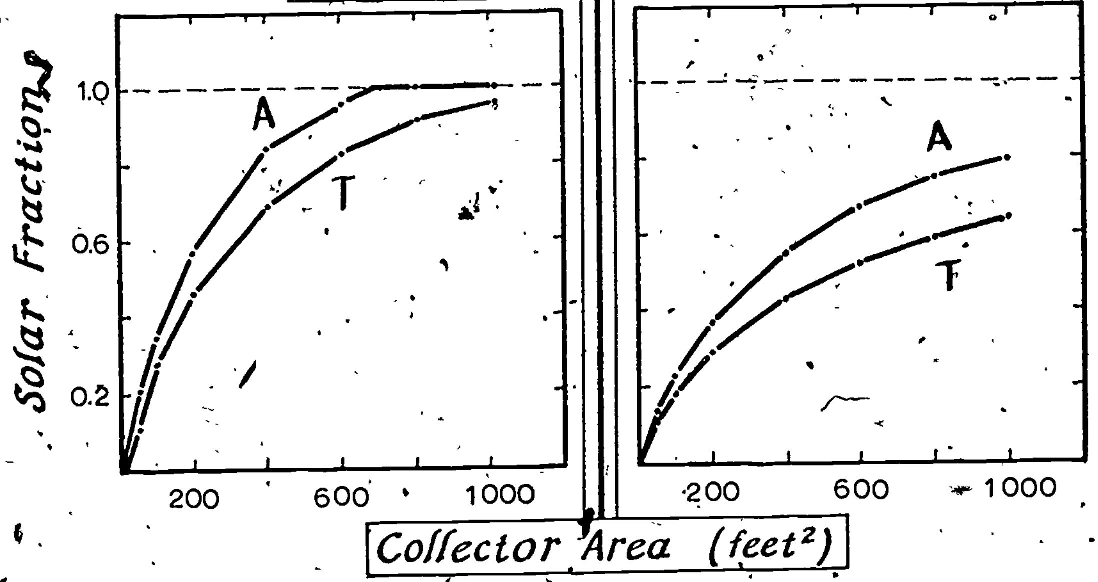
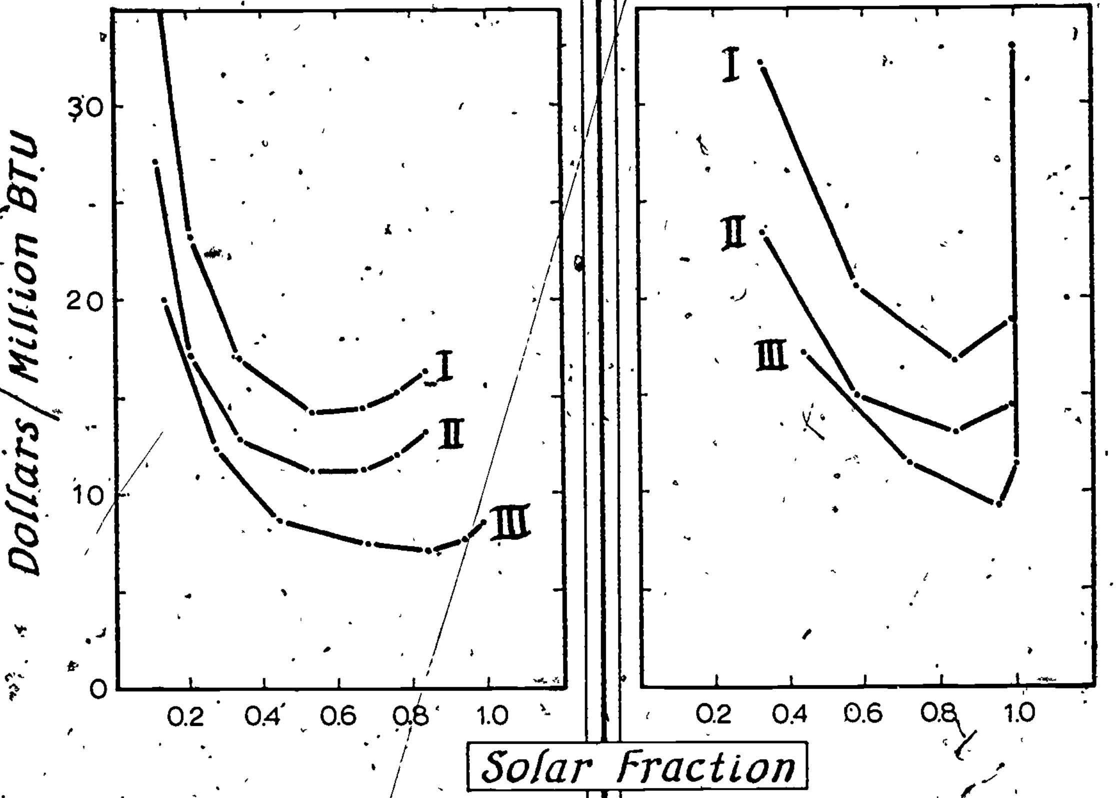


LINCOLN | LOS ANGELES

AVERAGE COST CURVE



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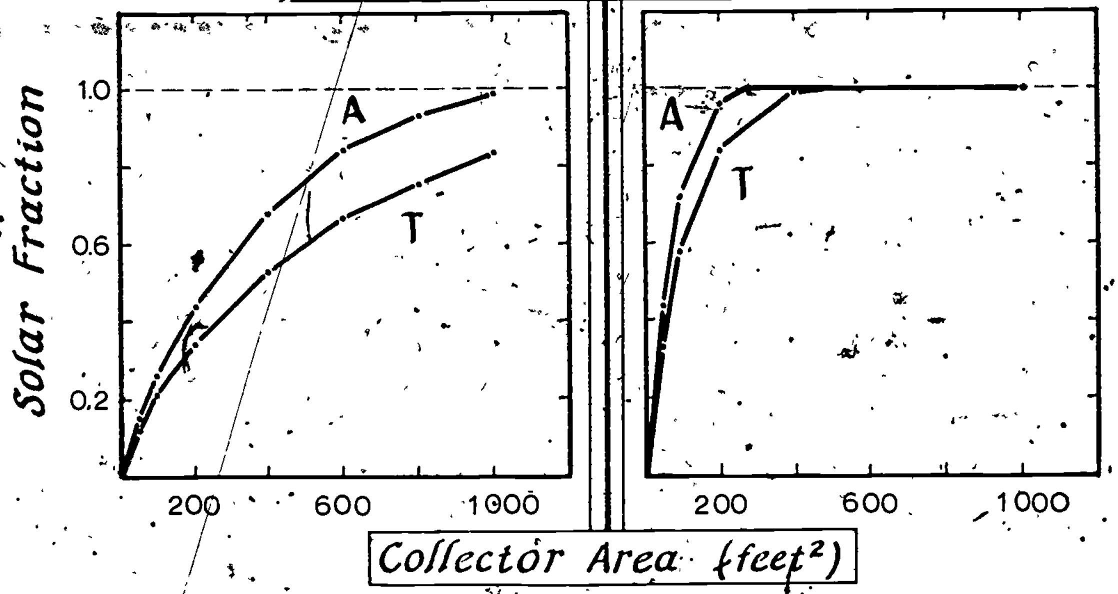
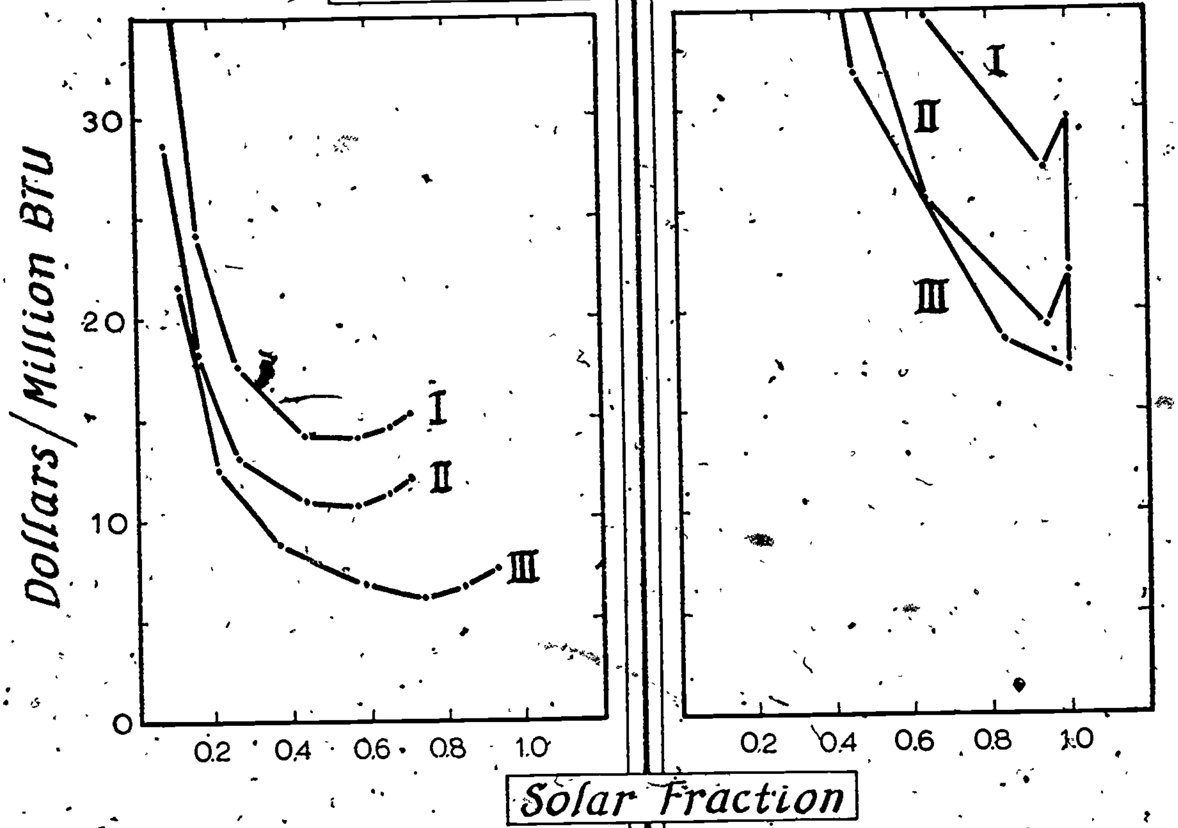


MADISON - MIAMI

AVERAGE COST CURVE



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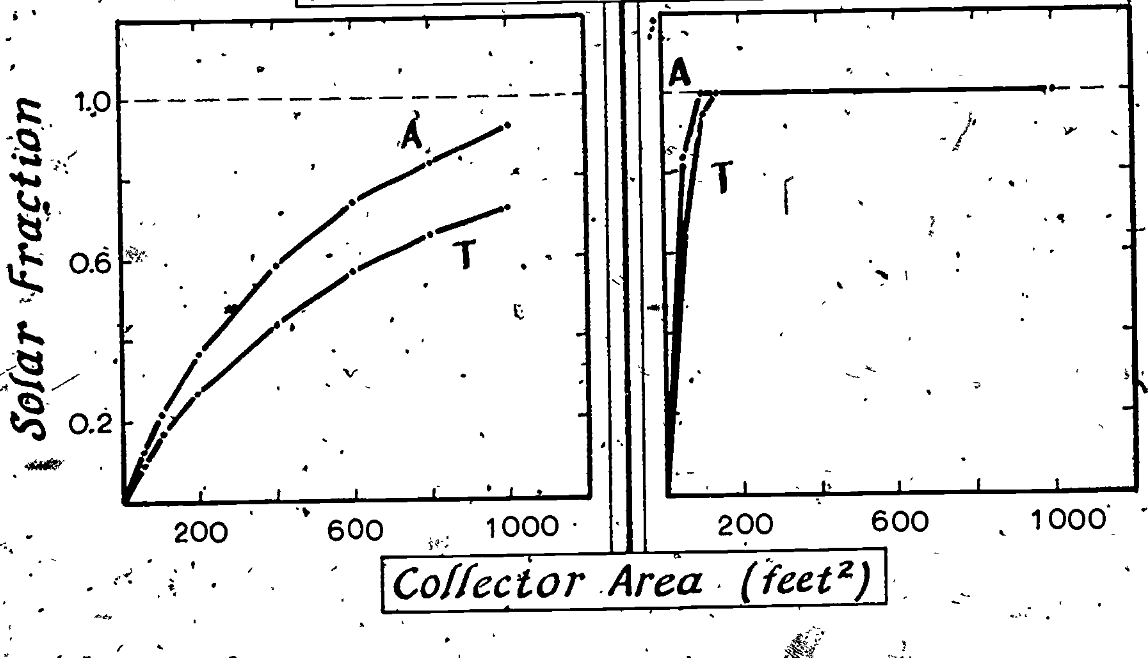
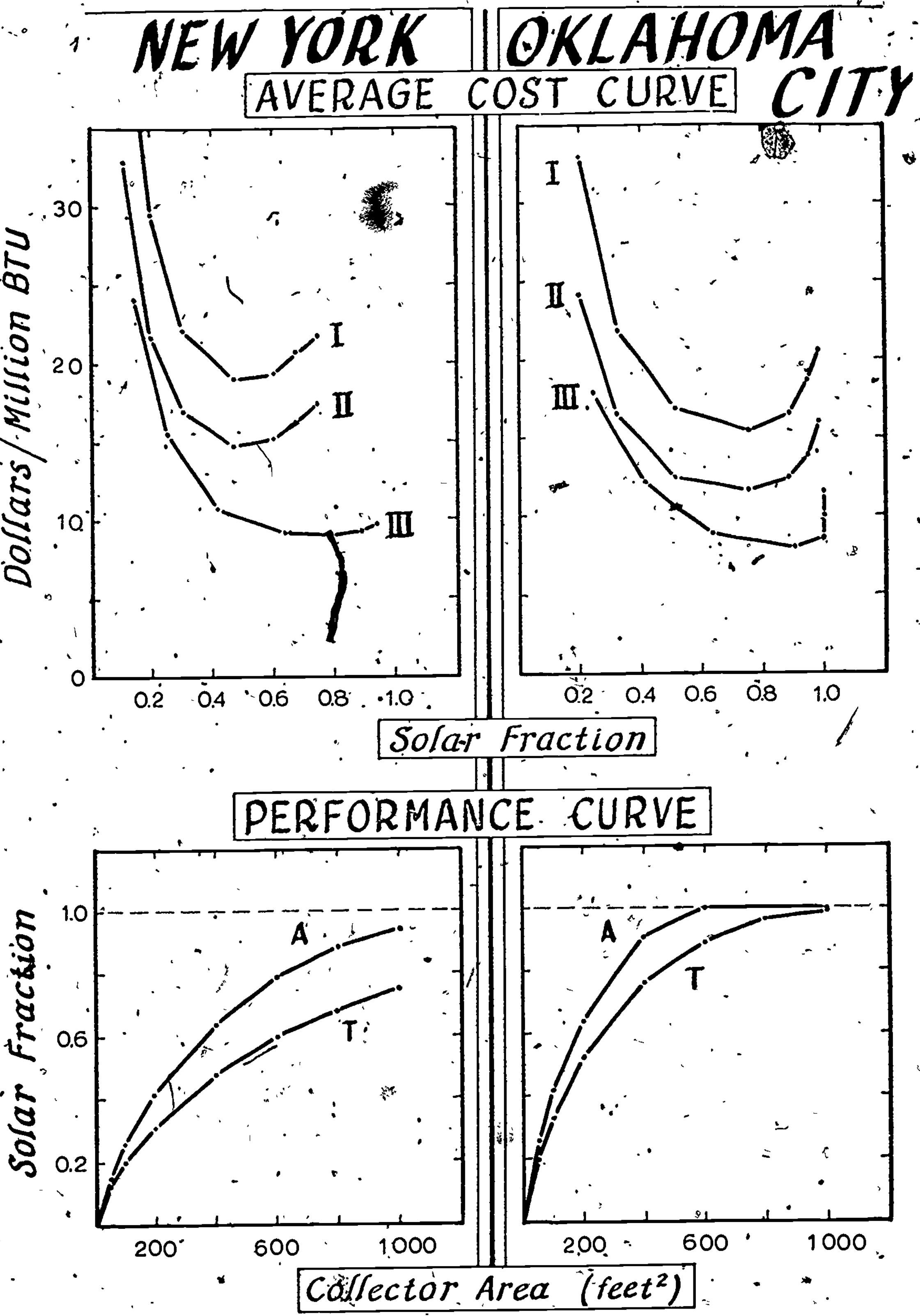
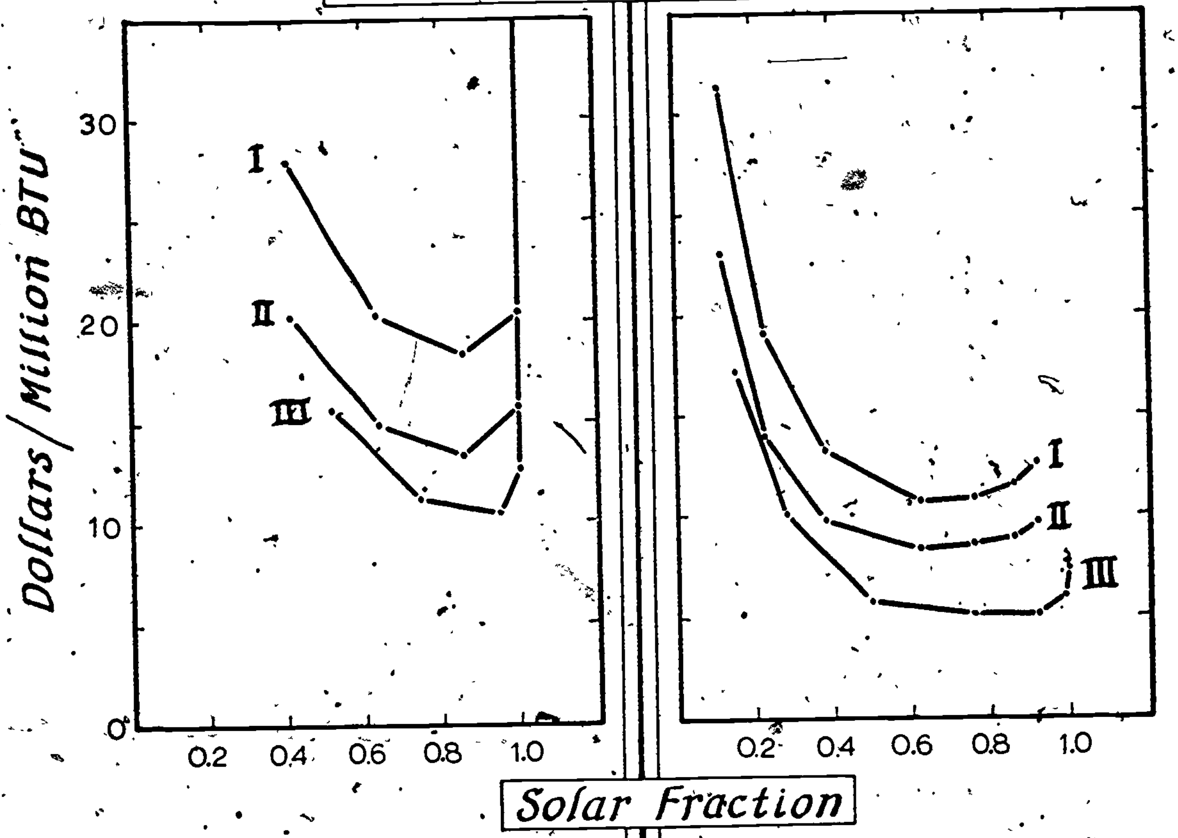


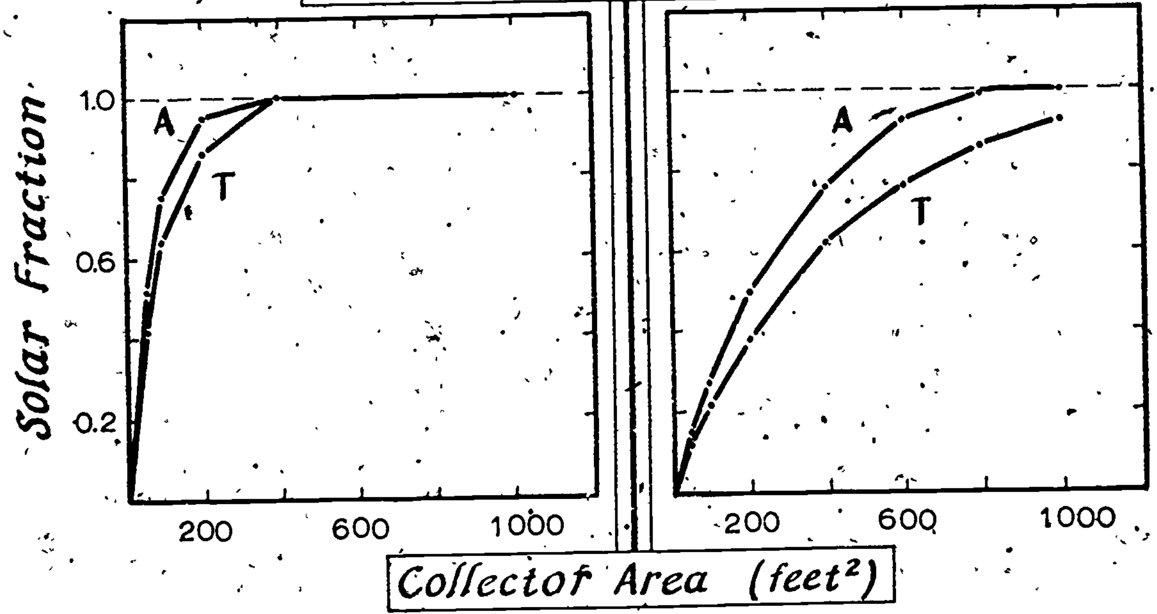

NEW YORK
OKLAHOMA CITY
AVERAGE COST CURVE
Dollars*/Million BTU
0
10
20
30
I
II
III
0.2
0.4
0.6
0.8
1.0
Solar Fraction
PERFORMANCE CURVE
Solar Fraction
0.2
0.6
1.0
A
T
200
600
1000
Collector Area (feet²)

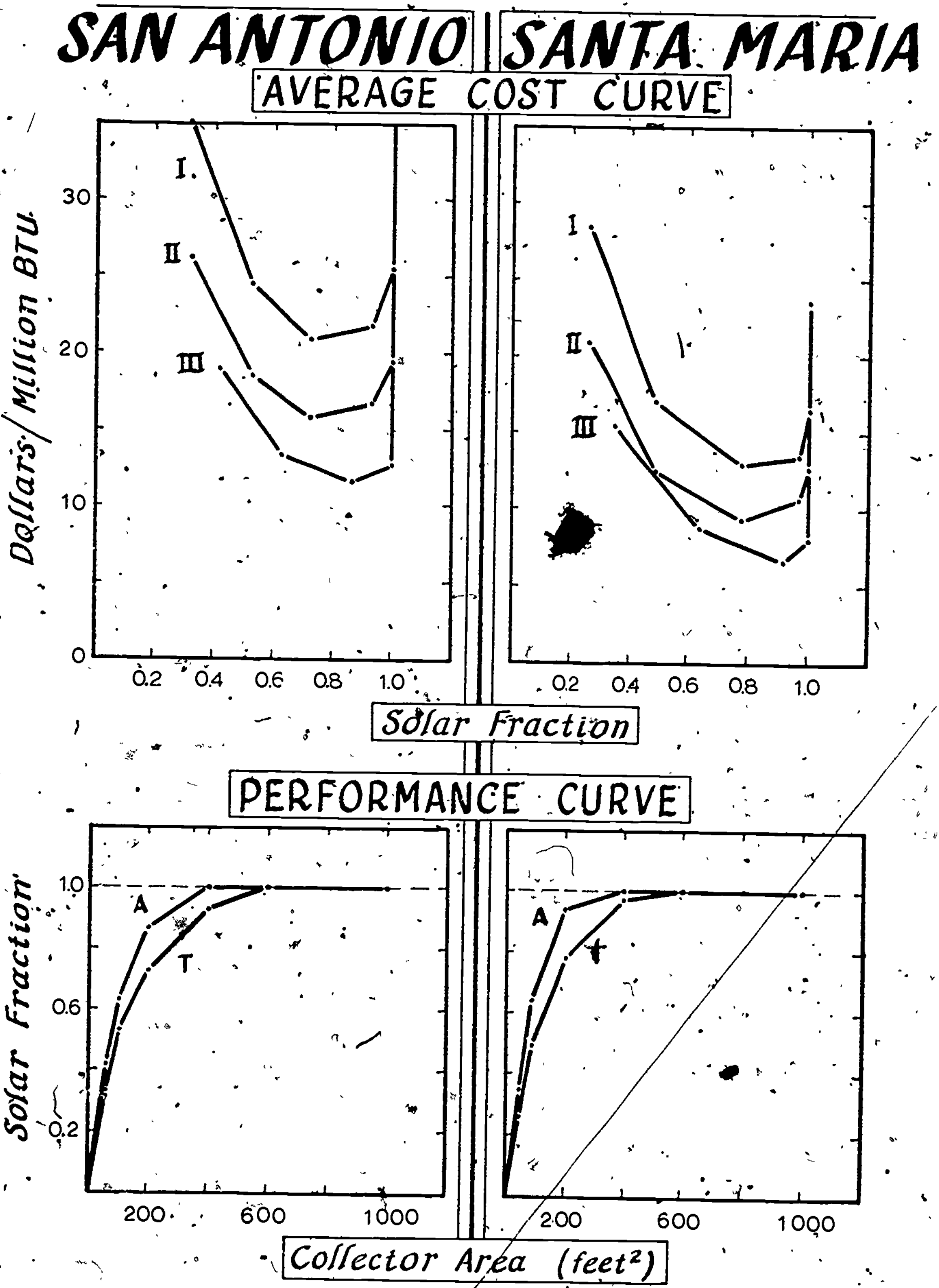
PHOENIX | RAPID CITY

AVERAGE COST CURVE



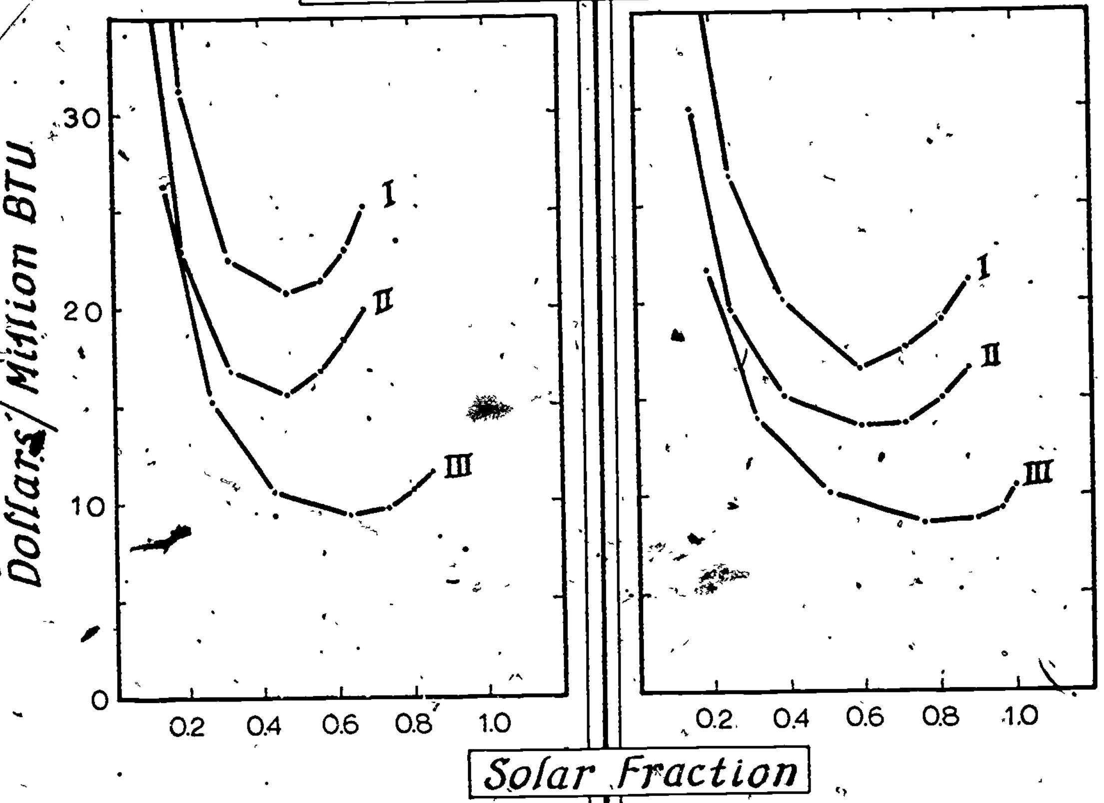
PERFORMANCE CURVE



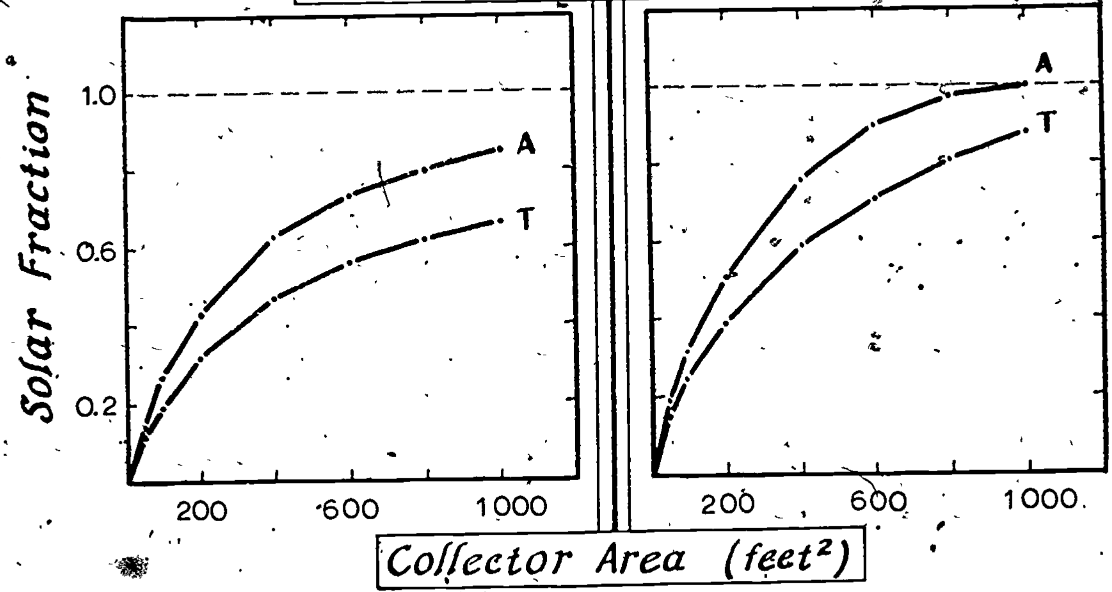

SAN ANTONIO
SANTA MARIA
AVERAGE COST CURVE
Dollars/Million BTU
30
20
10
0
I.
II
III
0.2
0.4
0.6
0.8
1.0
Solar Fraction
PERFORMANCE CURVE
Solar Fraction
1.0
0.6
0.2
A
T
200
600
1000
Collector Area (feet²)

SEATTLE WASHINGTON

AVERAGE COST CURVE



PERFORMANCE CURVE



APPENDIX B

1975 Costs of Conventional Heating Fuels in the 20 Cities

Table: 1975 Costs of Conventional Heating Fuels

City	Average* Fuel Cost ($/10⁶ BTU)		
	Electricity	Oil	Gas
Albuquerque, New Mexico	7.4	—	3.2
Atlanta, Georgia	5.5	4.1	1.6
Boise, Idaho	5.0	—	2.9
Boston, Massachusetts	11.5	4.7	4.1
Charleston, South Carolina	8.4	4.6	2.8
Cleveland, Ohio	5.1	4.3	2.1
Grand Junction, Colorado	6.3	—	1.0
Indianapolis, Indiana	6.7	4.2	1.8
Lincoln, Nebraska	3.9	—	1.9
Los Angeles, California	8.0	—	2.4
Madison, Wisconsin	5.7	4.2	2.1
Miami, Florida	8.6	—	1.6
New York, New York	20.0	4.6	5.5
Oklahoma City, Oklahoma	4.9	—	1.3
Pheonix, Arizona	7.5	—	2.1
Rapid City, South Dakota	3.8	—	1.8
San Antonio, Texas	5.4	—	1.3
Santa Maria, California	6.3	—	2.4
Seattle, Washington	2.9	—	3.2
Washington, D.C	8.3	4.6	3.5

[*] These cost numbers represent the average amount that would be paid per unit of heat energy received for each fuel. Furnace efficiencies of 67% for gas, 62% for oil and 100% for electricity have been used in the calculation of these numbers. Also, rate steps which lower the unit energy costs with increasing consumption have been incorporated to compute the averages. The information for each fuel was obtained from suppliers in each city.

APPENDIX C

Solar Equipment Producers Contributing to the Cost Study and Reviewers of The Draft Version of this Report

Solar Equipment Producers Contributing to the Cost Study

1. Corning Glass Works, Corning, New York
2. Energex Corporation, Las Vegas, Nevada
3. Energy Systems Inc., El Cajon, California
4. InterTechnology Corporation, Warrenton, Virginia
5. Owens-Illinois, Inc., Toledo, Ohio
6. Pittsburgh Plate Glass Industries, Inc., Pittsburgh, Pennsylvania
7. Ray Pack, Inc., Westlake Village, California
8. Revere Copper and Brass, Inc., New York, N.Y.
9. Solaron Corporation, Denver Colorado
10. Solar Research, Granada Hills, California
11. Solar Utilities Company, San Diego, California
12. Sunworks, Inc., Guilford, Connecticut

Reviewers of The Draft Version of this Report

W. A. Beckman and J. A. Duffie—University of Wisconsin, Madison, Wisconsin

Al Blair—Los Alamos Scientific Laboratory, Los Alamos, New Mexico

Paul P. Craig—University of California, Systemwide Administration, Berkeley, California

David Eaton—Lyndon B. Johnson School of Public Affairs, University of Texas, Austin, Texas

Marcel R. Harper—RANN directorate, National Science Foundation, Washington, D.C.

George O. G. Löf—Solaron Corporation, Denver, Colorado

Norman Lutkefeder—Solar Energy Branch, Federal Energy Administration, Washington, D.C.

Owen McGarity—Clarendon, Texas

Abel Wolman, Jared Cohon, Charles ReVelle, and John Boland—The John Hopkins University, Baltimore, Maryland

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