ALTERNATIVE ELECTRICAL ENERGY SOURCES FOR MAINE

W.J. Jones M. Ruane

Appendix F

SOLAR ENERGY CONVERSION

J. Geary W.J. Jones

Prepared for the Central Maine Power Company.

Report No. MIT-EL 77-010
MIT Energy Laboratory
December 1977

This appendix is one of thirteen volumes; the remaining volumes are as follows: A. Conversion of Biomass; B. Conservation; C. Geothermal Energy Conversion; D. Ocean Thermal Energy Conversion; E. Fuel Cells; G. Conversion of Solid Wastes; H. Storage of Energy; I. Wave Energy Conversion; J. Ocean and Riverine Current Energy Conversion; K. Wind Energy Conversion, and L. Environmental Impacts.

Acknowledgments

Initial literature reviews and drafts of the various technical appendices were prepared by the following people:

Appendix A	Conversion of Biomass - C. Glaser, M. Ruane
Appendix B	Conservation - P. Carpenter, W.J. Jones, S. Raskin, R. Tabors
Appendix C	Geothermal Energy Conversion - A. Waterflow
Appendix D	Ocean Thermal Energy Conversion - M. Ruane
Appendix E	Fuel Cells - W.J. Jones
Appendix F	Solar Energy Conversion - J. Geary, W.J. Jones
Appendix G	Conversion of Solid Wastes - M. Ruane
Appendix H	Storage of Energy - M. Ruane
Appendix I	Wave Energy Conversion - J. Mays
Appendix J	Ocean and Riverine Current Energy Conversion - J. Mays
Appendix K	Wind Energy Conversion - T. Labuszewski
Appendix L	Environmental Impacts - J. Gruhl

Numerous people shared reports and data with us and provided comments on the draft material. We hope that everyone has been acknowledged through the references in the technical sections, but if we missed anyone, thank you!

Ms. Alice Sanderson patiently weathered out many drafts and prepared the final document with the assistance of Ms. Dorothy Merlin.

Preface

The Energy Laboratory of the Mass. Inst. of Tech. was retained by the Central Maine Power Company to evaluate several technologies as possible alternatives to the construction of Sears Island #1 (a 600 MWe coal fired generating plant scheduled for startup in 1986). This is an appendix to Report MIT-EL 77-010 which presents the results of the study for one of the technologies.

The assessments were made on the basis that a technology should be:

1) an alternative to a base-load electric power generation facility. Base-load is defined as ability to furnish up to a rated capacity output for 6570 hours per year.

2) not restricted to a single plant. It may be several plants within the state of Maine. The combined output, when viewed in isolation, must be a separate, "stand-alone" source of power.

3) available to deliver energy by 1985.

APPENDIX F

SOLAR ENERGY CONVERSION

Page

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

Solar energy is the ultimate source of most of our present and future energy supplies including fossil fuels, biomass, winds, hydropower and tidal and ocean currents. Nuclear and geothermal energy are the two notable exceptions that do not trace their primary energy to the sun's radiation. This appendix considers the potential of directly converting solar energy (i.e., radiation) to a useful energy form, without waiting for it to be naturally converted to hydrocarbons by photosynthesis (coal, oil) or potential or kinetic energy by evaporation of water (hydro), heating of air masses (wind), or heating of the oceans (currents and ocean thermal).

Solar radiation presents several problems. It is diffuse, time varying and subject to uncontrollable interruptions. Because it is diffuse, large collection areas or concentration devices are needed to accumulate significant amounts of energy. Because it is time varying and can be randomly interrupted, solar devices, to compete with conventional systems, need back-up systems in the form of storage or independent energy supplies. Solar devices without back-up can make a contribution to energy sources.

Devices and systems are being developed which convert solar radiation to high-temperature heat (replacing large fossil- or nuclear-fueled facilities), direct current electricity (for both large and small applications) and low-temperature heat (for space conditioning).

Although these devices and systems are technically feasible, their economic viability is less clear. In order to ascertain whether solar technologies are competitive with fossil- or nuclear-fueled technologies, several steps of analysis are needed. These must be performed in a site-specific manner since the availability of solar radiation, the need for certain energy forms and the cost of competing technologies all depend on location. Even when technically feasible and economically attractive, some solar technologies may not be utilized due to legal or institutional barriers.

This appendix will analyze the potential energy contribution of solar energy conversion in Maine, with the objective of assessing its impact on the supply and demand of electricity. The remaining sections will consider both centralized conversion schemes (e.g., large solar energy plants) and dispersed schemes (e.g., single dwelling equipment).

In writing about solar energy utilization, one is confronted with an enormous amount of written material. Since the mid-forties, there has been a steady flow of journal articles, books, and symposia proceedings. Within the last few years, the flow has become overwhelming as the government funds more projects which require more reports. Many of these reports are concerned with specific experiments and the information is too detailed to be of use in gaining a general understanding. The same can be said for many of the journal articles and symposium papers which deal with technical improvements to standard designs. There are references to some of these articles where appropriate. Useful references which give a general overview are:

1. The Solar Home Book (Anderson, 1976)
2. Solar Heated Houses (Massdesign, 1975)
3. Solar Energy Utilization for Heating and Cooling (Yellott, 1976)
4. Direct Use of the Sun's Energy (Daniels, 1964)
5. Buying Solar (FEA, 1976)

2.0 SOLAR INSOLATION

2.1 General

The design of an energy conversion system using solar energy requires knowledge of the solar insolation on a daily and seasonal basis. Solar insolation is defined as the amount of solar energy falling on a specified area in a specified time, but unfortunately the units of measurement are not standardized. The following conversions will be helpful (Duffie & Beckman, 1974, p. 372).

1 langley = 1 calorie/centimeter^2(cal/cm^2)
= 41.86 kilojoules/meter^2(KJ/m^2)
= 11.63 watt hour/meter^2 (Wh/m^2)
= 3.69 Btu/ft^2

Using spherical geometry the theoretical amount of solar radiation incident upon a horizontal surface can be computed as a function of latitude, day of year, and time of day (Figures 2.1 and 2.2).

Monthly and Latitudinal Variation of
Clear Day Solar Insolation on Horizontal Plane
in Northern Hemisphere

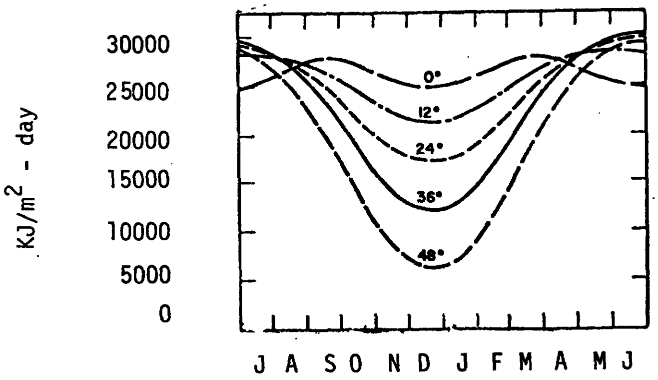
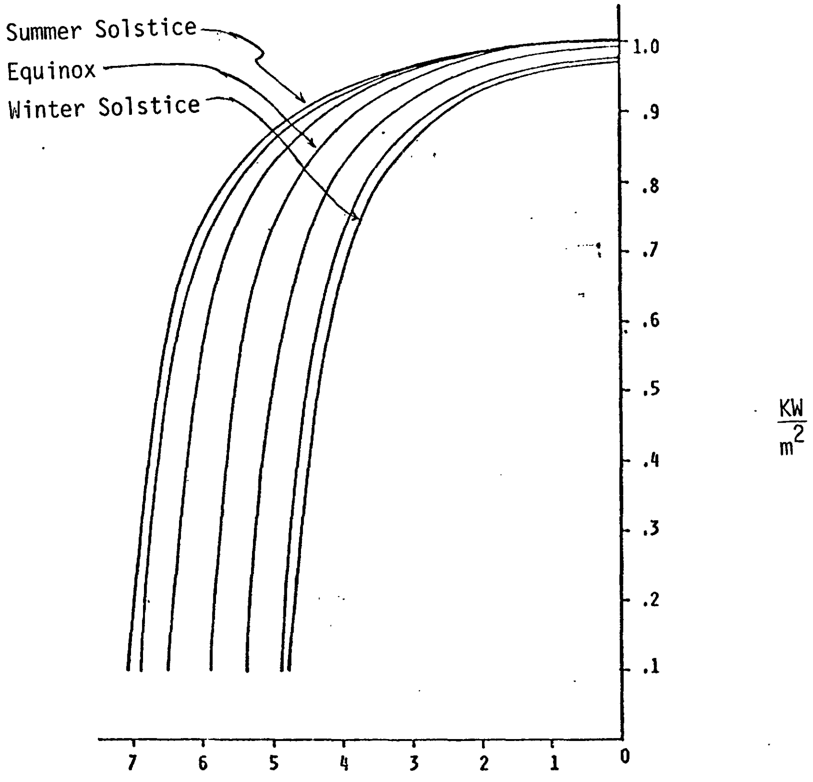


Figure 2.1

from (Duffie & Beckman, 1974, p. 39)

Diurnal Variation of Solar Radiation at 35°N Latitude



Hours from Noon

Figure 2.2

The solar radiation which actually reaches the ground at any time may be significantly less than the theoretical value, depending on the attenuation and dispersion properties of the atmosphere. Clouds, dust, water vapor and air pollutants combine to absorb and reflect much of the energy.

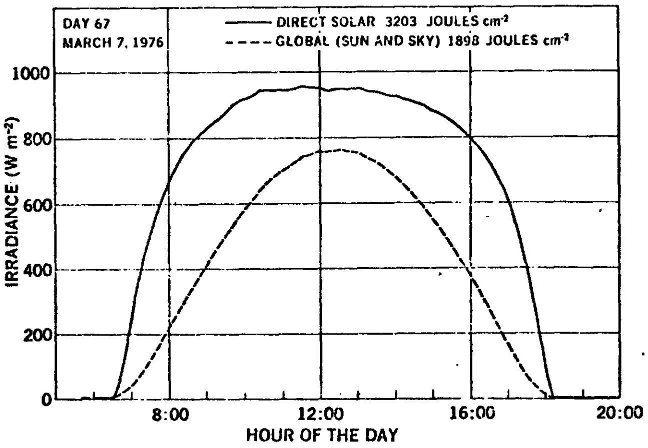


Figure 2.3 Ten-Minute Averages of Direct Solar (NIP) and Global (Pyranometer) Irradiance on a Clear Day

from (Thomas and Thekackara, 1976, p. 341)

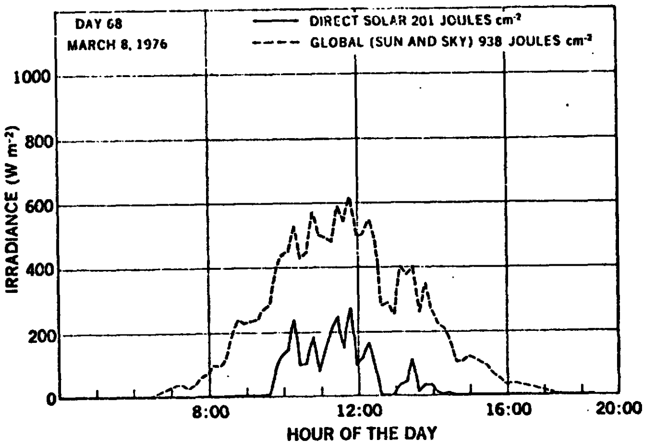


Figure 2.4 Ten-Minute Averages of Direct Solar (NIP) and Global (Pyranometer) Irradiance on a Cloudy Day

from (Thomas and Thekackara, 1976, p. 341)

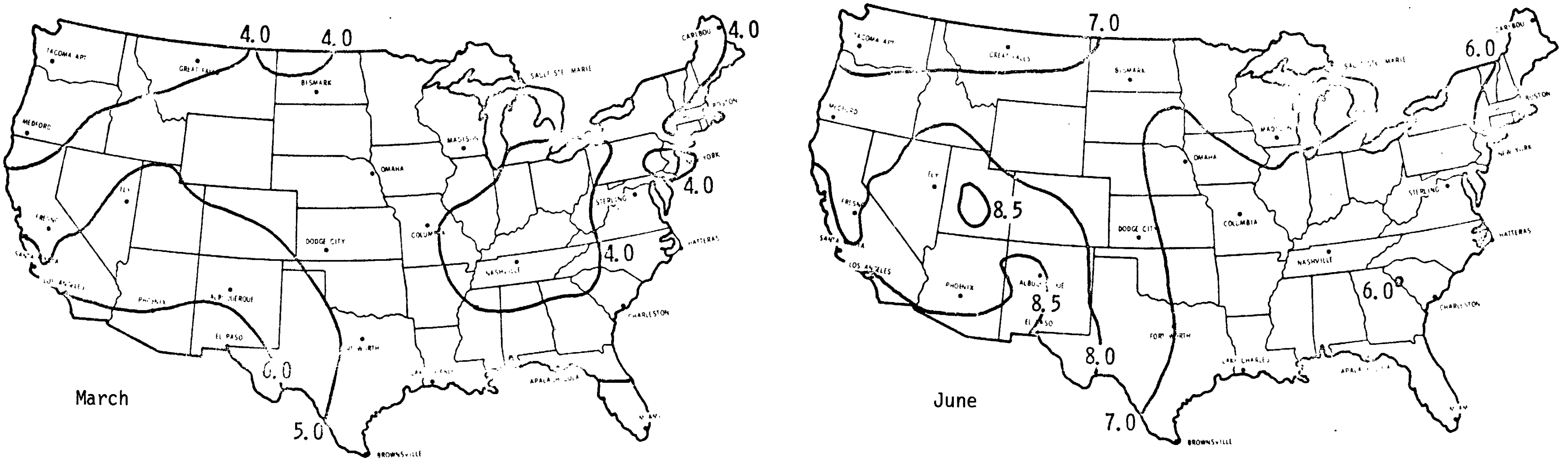
The composite effects of latitude and weather are shown by monthly average isolines of solar insolation (Figure 2.5). In general, insolation increases with decreasing latitude, but there are many local irregularities. The effects of coastal influences are seen in New England data (Figure 2.6).

Another important aspect of solar radiation is the angle at which the rays strike the earth. For direct, or beam radiation (radiation which is seen as coming directly from the sun's disc), the angle of incidence on a horizontal surface is the height of the sun in the sky. Indirect, or diffuse, radiation, which has been reflected off water vapor, air pollutants, etc., has rays that are no longer parallel to the initial beam radiation. Indirect radiation strikes a horizontal surface from all angles of the sky. The average ratio of direct to indirect radiation depends on the weather patterns of an area and can be measured by comparing the solar radiation incident on a plate held perpendicular to the sun's rays with the solar radiation incident on a horizontal plate. Holding the plate perpendicular to the sun's rays will collect the maximum amount of direct radiation per unit area. The amount of diffuse radiation would be collected on both plates. Figure 2.7 graphs values of direct normal radiation for comparison with Figure 2.5.

There are two types of solar radiation measurements commonly made on the ground -- direct and global. Direct irradiance, that is irradiance on a surface normal to the sun's rays, is measured by a "Normal Incidence Pyrheliometer" (NIP) mounted on a heliostat which tracks the sun. A "pyranometer" measures the global (sun and sky) irradiance. For the global measurement the instrument is stationary and parallel to the earth's surface. Both instruments operate on the principle of the thermopile -- an electrical voltage is generated which is recorded on a magnetic tape or strip chart.

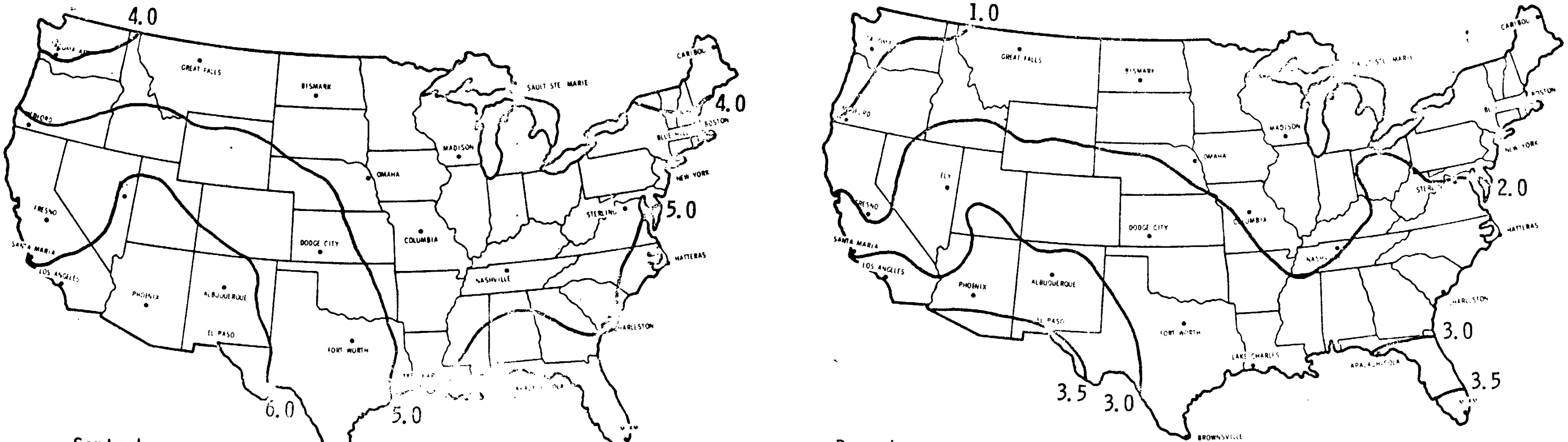
Figures 2.3 and 2.4 show the type of data obtained from these instruments. The x-axis is time in hour of the day and y-axis is irradiance in watts per square meter. The data points are 10-minute averages. The continuous curve gives the direct solar (NIP) readings and the dashed curve gives the global readings. The totals for the day are given to the top right of the figures. The NIP reading is always higher than the pyranometer reading on a clear day, (Figure 2.3), but on cloudy days (Figure 2.4) the pyranometer readings are higher because of the reflection from the clouds. Clouds are powerful attenuators of solar radiation and the presence of clouds brings the direct irradiation to a very low value.

The ratio of direct to indirect radiation becomes important in designing solar collectors that have a high cost per square foot or where high temperatures are required. For places with mostly clear skies, systems can be used to keep the collectors perpendicular to the sun's rays by tracking the sun along its path in the sky. At these places, the systems may include features that focus parallel beams of light onto a small collector area. In places with frequently overcast weather, tracking and focusing are not as useful in improving the performance of the collectors. Neither tracking nor focusing can enhance the collection of diffuse radiation. For collectors that have a fixed orientation, a design rule of thumb is that they should face south and be tilted at the latitude plus 10° for optimum winter collection (Anderson, 1976, p. 176).



March

June



September

December

Mean Daily Total (Direct & Indirect) Horizontal Surface Radiation

Kwh/m^2

Figure 2.5

from (Boes, et al., 1976, pp. 247-258)

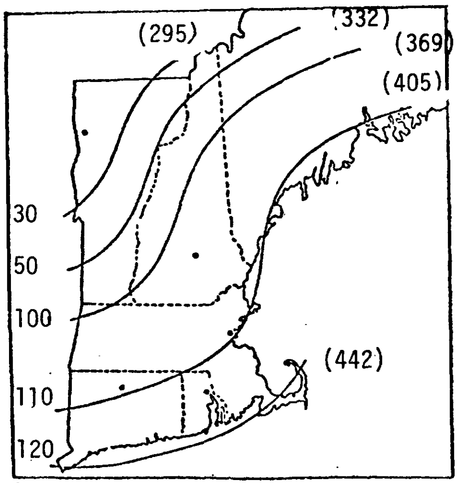
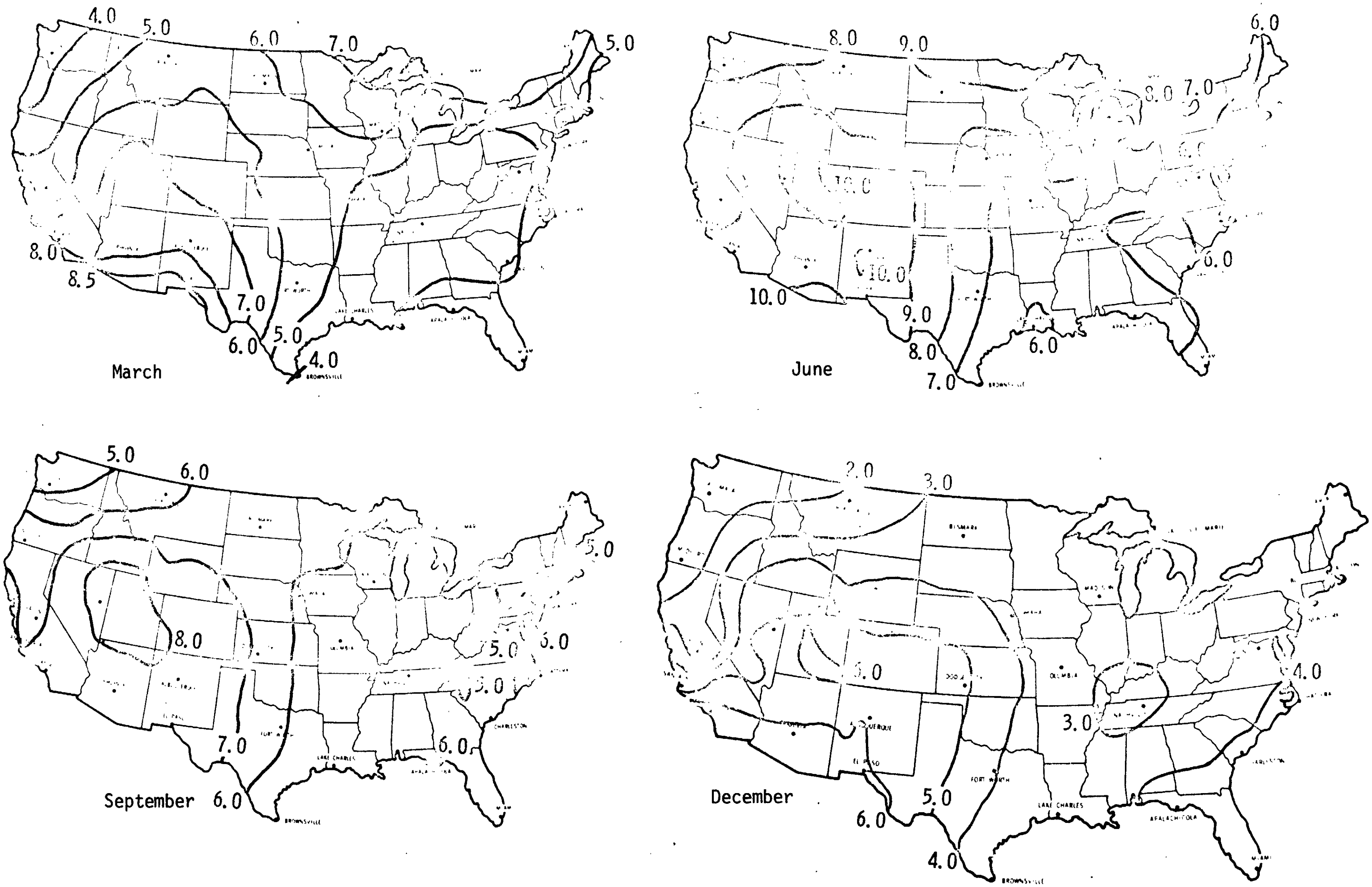


Figure 2.6 Average Total Solar Radiation in Langleys/Day
December 1971 - 1972

from (Atwater, et.al., 1976, p. 5)



March

June

September

December

Mean Daily Direct Radiation
Kwh/m^2
Figure 2.7

from (Boes, et al., 1976. pp. 247-258)

Monthly average solar insolation values for Orono, Portland and Waterville, Maine include both beam and diffuse radiation (Table 2.1). Table 2.1 does not reflect the day-to-day variability due to weather.

Table 2.1

Solar Insolation Data for Maine
(Btu/ft^2/day)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Portland*												
horizontal surface	559	864	1295	1504	1890	1982	2063	1795	1409	1023	557	504
surface at 60° tilt to south	1196	1452	1748	1655	1796	1725	1857	1938	1733	1575	1132	1154
Waterville*												
horizontal surface	530	859	1390	1492	1834	1878	1964	1735	1338	922	507	458
surface at 60° tilt to south	1135	1443	1876	1841	1742	1633	1785	1874	1845	1491	994	1049
Orono**												
horizontal surface	493	745	1139	1513	1716	1893	1852	1593	1264	937	476	399
surface at 60° tilt to south	1085	1294	1523	1570	1480	1514	1551	1533	1517	1476	952	943

*data from Maine Office of Energy Resources and NEEMIS study

** historical data [Albert & Holt, 1976, p.42]

2.2 Energy Demand/Available Sunshine

The day/night cyclic variation in sunlight can be derived from calculated solar position and the seasonally varying properties of a standard atmosphere. Economic analysis requires, in addition, performance prediction based on knowledge of the historical variations of solar insolation during daylight hours for each proposed site.

Data, such as illustrated in Figures 2.3 through 2.7 can give some insight into long-term (seasonal or yearly) average behavior of a solar energy system under local atmospheric conditions. Such data are useful but far from sufficient. Short-term fluctuations (reduced intensity) of sunlight reaching collectors due to overcast may last for days. Broken cloud cover may block the sun for only a fraction of an hour.

Programs for the collection of standardized weather and insolation data of sufficient detail and for several geographical locations of the USA are being established by the U.S. Department of Energy, (Newspace, 1974; Boer, 1976; ERDA, 1976; French, 1977). No results concerning New England or Maine are yet available.

An analysis of sunshine availability for New England was conducted by Prof. A. Dietz of the Mass. Inst. of Tech., (Dietz, 1954), in connection with the series of experimental MIT solar houses. The data collected for the experiments were used for space heating studies. The summer months information is absent. The available data are, however, quite pertinent and adequate for the analysis which follows.

In Figure 2.8, the 57-year U.S. Weather Bureau monthly average figures, curve #2, for percent of sunshine in the Boston, Mass. area are plotted together with the corresponding observed numbers, curve #1, for 1949-50. The seasonal variation from the rather smooth 57-year average is quite marked.

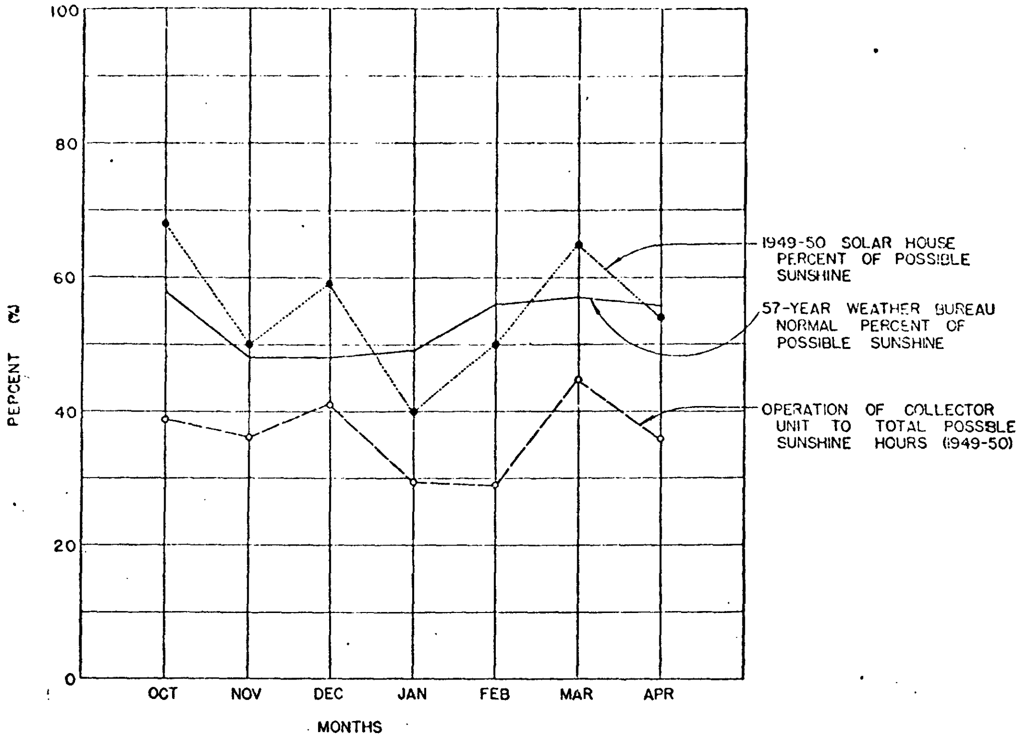


Figure 2.8 Percent Sunshine of Possible Sunshine and Time of Operation of Collector Unit

from (Dietz, 1954)

On this same figure is plotted curve #3 the percent of time during 1949-1950 that the collectors on the MIT solar house were in operation as compared with the possible total sunshine hours (assuming no overcast during the entire season). Although this curve in general follows the percent sunshine curve for 1949-1950, there is a noticeable difference in February showing that the percent available sunshine for that month was not a reliable guide to the amount of solar energy collected.

In the absence of a definite explanation for the difference, one may speculate that the collector or recording systems were defective, wind, snow and/or temperature conditions impaired operation of the collectors or a variety of other reasons. We will assume the "best case" and continue our discussion on the premise that available sunshine and collectable sunshine can have a constant relationship.

Figures 2.9a and 2.9b give the distribution of days of various degrees of sunshine in January and April for the period 1940-1950. These weather data show that the chances of having very sunny or very overcast days are much better than having intermediate days.

Figure 2.10 presents another analysis of percentage sunshine figures, which shows the probable sequence of days of high (75-100) percent sunshine, which can be expected to provide an excess of energy available to be stored for future use, and the probable sequence of days of low (0-25) percent sunshine, which can be expected to be of little or no use in providing solar derived energy.

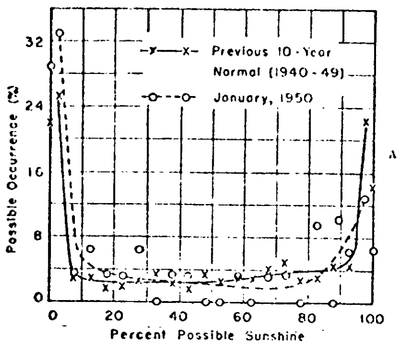


Figure 2.9a
Probable Distribution of Possible
Sunshine for the Month of
January

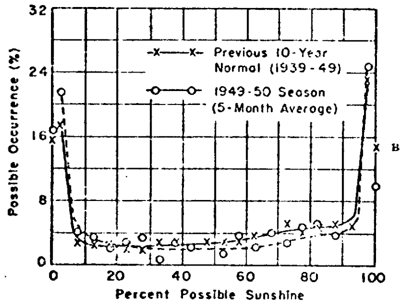


Figure 2.9b
Probable Distribution of Possible
Sunshine for the Period October through April

from (Dietz, 1954)

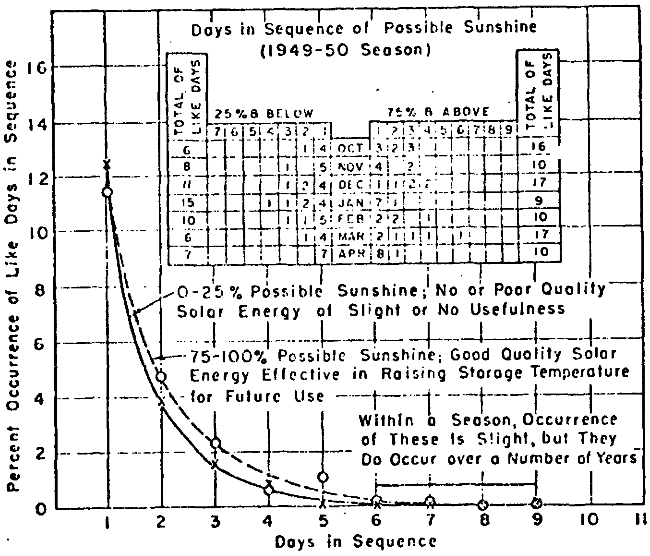


Figure 2.10

Probability of Sequences Occurring of Like Days for the Total Number of Days Considered (10-Year Average for October through April)

Source: Dietz, 1954.

Further information on the probable sequences of periods of no-collection of solar energy is provided in Figure 2.11. The collection and no-collection periods, as recorded at the solar houses, were analyzed and the periods in hours of no collection were plotted. No periods of less than 14 hours are to be found because the shortest sunset-to-sunrise time during the period was close to 14 hours.

Of the total no-collection time, nearly 50 percent is represented by periods of less than 48 hours, and nearly 90 percent by periods less than 72 hours. Periods ranging above 90 hours (roughly 4 days) are rare. They do, however, exist. Collection and storage for 6 sunless days would have been necessary in 1949-50 to meet all the requirements of a base-load type of electric power plant.

The data and analysis cited above hold for the particular weather conditions around Boston. They are indicative, however, of the kind of results one might expect in many parts of Maine.

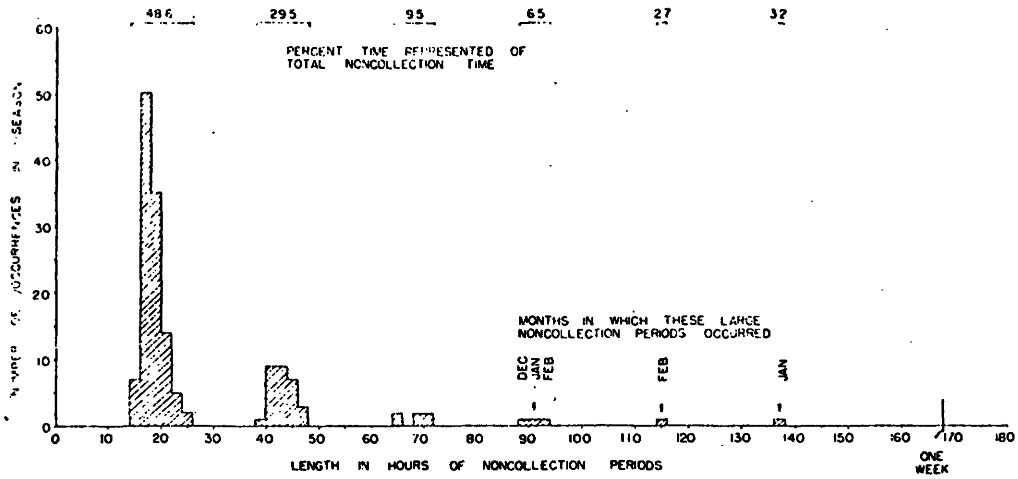


Figure 2.11

Distribution of Periods of No Collection of Solar Energy (1949-1950)

Source: Dietz, 1954.

It is clear that if one requires a solar (sunshine) energy electric power plant to match the performance of the proposes Sears Island power plant, enough energy must be collected and stored not only for the nighttime but also additional amounts sufficient to provide electricity during the periods of several sunless days in a row which do occur frequently throughout the year.

There is, in addition, the requirement (as revealed by the statistical history Figure 2.10) that, once exhausted, the storage ought to be recharged within three days (20 to 33 collection hours, depending upon the season) in order for the plant to be functional during the next cloudy spell.

2.3 Reliability/Electric Utilities

On a statistical performance/demand basis solar energy facilities can present a "capacity credit" of "reliable" power within a given utility system. This "reliable" power can be expressed as a fraction of the rated capability per facility. This concept was studied (Justus, 1976) in connection with dispersed wind energy generation stations. A group of wind energy powered electricity generation stations was considered as an array and, based on wind data, calculations were made to estimate "capacity credit" for an array. The study was exclusively for wind powered machines and is discussed in some detail in Appendix K, "Wind Energy Conversion" of the overall analysis of alternative electric energy sources for Maine.

There are current investigations which should result in a methodology for arriving at "capacity credit" equivalencies for a number of dispersed solar energy (thermal and photovoltaic) stations. Preliminary results seem to indicate that a number of dispersed small solar powered facilities, when considered in concert against a plurality of various types of load demands, can present an equivalency to a single bulk central conventional power plant, albeit the "capacity credit" figure is less than the total rated capability, just as it is for a central station plant.

2.4 "Base-load" Characteristics

Terrestrial solar energy is both time variant and probabilistic (night/day - clear/cloudy). In order for a solar energy powered electricity generating station to possess the "base-load" type of capability of the proposed Sears Island power plant, it must:

a collect sufficient solar energy, when it is available, equal to that which is to be used at once, plus that which is necessary for storage (in some recoverable form) to meet the demand for electricity when collectable solar derived energy is not available.

or

b include either at the solar energy facility, or indirectly, as part of the utility system, "committed" back-up generation capacity which operates from conventional fuels or hydroelectric sources.

It is not, however, necessary that a solar energy facility possess "stand-alone" characteristics in order to be a useful part of the electricity supply system. The use of solar energy on an "as available only" basis can diminish the need for electricity produced at conventional plants, hence reduce the consumption of conventional fuels, thus conserving non-renewable resources and lessening the environmental impacts attributed to nuclear and fossil fuels utilization.

The reduced demand for conventionally generated electricity (as a result of solar derived electricity generation) does not mean that the inventory of the conventional (fossil or nuclear fueled) central station capacity, required to service a consumer group, can be similarly reduced; back-up capability must exist, as it must exist for all types of power plants. It does not have to be on a one-to-one basis.

2.5 Collector Area

A major consideration in the design and performance of any solar system is the geographical aspect of the collector location. Land in valleys or on the shady sides of hills is not suitable. In addition, areas near the coastline where fog and haze are frequent have less value as suitable sites.

The areas that survive insolation requirements must then be subject to scrutiny to determine land damage (the collectors shade the earth below them), competitive uses for the land, and finally economics.

3.0 SOLAR ENERGY TECHNOLOGIES

The technologies for converting solar radiation into usable energy range from elementary to sophisticated. The simplest methods involve passive architectural design elements such as building orientation, window placement, shading, and insulation. Architectural design will not be considered here. Only new houses or houses undergoing fairly major renovation can make effective use of such changes. Passive architectural design changes are likely to require decades to make any significant impact on Maine's electricity use. Since architectural design plays a major role in the energy requirements of a building, it is considered briefly under space heating and cooling.

As can be seen from Figure 3.1, the use of solar technologies is dependent on the temperatures produced. We will consider four classes of solar technology, three of which produce heat and the fourth which produces electricity directly. The heat producing technologies are of interest because their heat can be converted to electricity or can replace electricity now used in heating.

3.1 Solar Space and Water Heating

Most systems for solar space and water heating make use of the fact that glass transmits (with little attenuation) radiation with wavelengths in the solar spectrum and is relatively opaque to radiation with very long or short wavelengths. (This is why glass is used in greenhouses.) It lets in visible light, but lets out relatively little heat.

An absorbing surface that is opaque to solar radiation absorbs radiation incident on it and re-emits some portion of the energy as long wavelength radiation, i.e., heat. Placing glass above an absorbing surface will cause the intervening air to be heated by the re-radiated energy.

Some buildings are designed to make direct use of the greenhouse effect by having large windows with southern exposure. These windows permit solar energy to enter the building where it is converted into heat. The windows trap the heat in the building by preventing long wavelength radiation from passing through them. Such buildings often have some method to sustain a constant temperature inside the building during periods of poor insolation and at night. Construction materials, such as concrete, or large masses of rocks, or water, can be used to store heat. The structure, rocks, or water are heated directly by the sun and act as storage. Shutters further restrict heat loss through the windows. These systems are known as <u>passive</u> systems since the heated space itself acts as the solar collector.

Alternatively, the more complex <u>active</u> systems have a solar energy collector which is separate from the heated space, placed on or near the heated building and use a fluid (air or liquid) which is circulated through the collectors and the living space. As in passive systems, a storage facility is used to retain heat for use during the night or during periods of poor insolation. The main distinction between active and passive systems is that active systems collect thermal energy in one place and then transfer the energy to another area where it is used while passive systems use the structure itself to collect their energy within the area of utilization.

One important element necessary to the success of both active and passive systems is good thermal insulation. In installing solar heating, the first step is always to ensure that the heating load has been reduced as much as possible through the use of insulation. Another element common to both systems is a back-up unit that supplies heat when there has not been enough solar radiation to heat the building or adequately charge the storage device. Common back-up units are oil furnaces, electric heaters and wood stoves.

Each type of system has its merits. The passive systems have lower installment costs and minimal maintenance requirements due to the simplicity of the heating system (provided major structural changes are not needed). This simplicity also makes them aesthetically appealing. However, the passive systems may require change in lifestyle since the building temperature is not easily regulated.

SOLAR COLLECTOR TECHNOLOGY

concentrating

non-concentrating

Temperature °F	APPLICATIONS
500 -	
-	Production of electrical power (fluids other than water)
400 -	Process steam
-	Evaporation in various processes
-	Digestion in paper pulp, kraft
-	Drying diatomaceous earth
-	Drying fishmeal, lumber
300 -	Alumina via Bayer's process
-	Drying farm products; canning of food
-	Evaporation in sugar refining
-	Fresh water by distillation
-	Drying of cement slabs
-	Most food drying
200 -	Space cooling by absorption refrigeration (lower limit)
-	Food drying (lower limit)
-	Space heating
-	Animal husbandry
-	Greenhouses (lower limit)
-	Mushroom growing
100 -	Hot baths
-	Swimming pools, biodegradation, fermentation
-	Fish hatching, fish farming

Figure 3.1 REQUIRED TEMPERATURES FOR VARIOUS APPLICATIONS

adapted from (Koomanoff, 1976, p. 210f)

Passive systems for trapping heat in a structure may, for example, include manually operated devices such as insulated shutters which must be opened in the morning and closed at night. Passive systems are most suitable for areas in which the sun shines brightly much of the time. There are some passive solar heated homes currently being built commercially in New England (Converse, 1975). More detailed descriptions of passive solar house designs can be found in (Anderson, 1976) and (Converse, 1975).

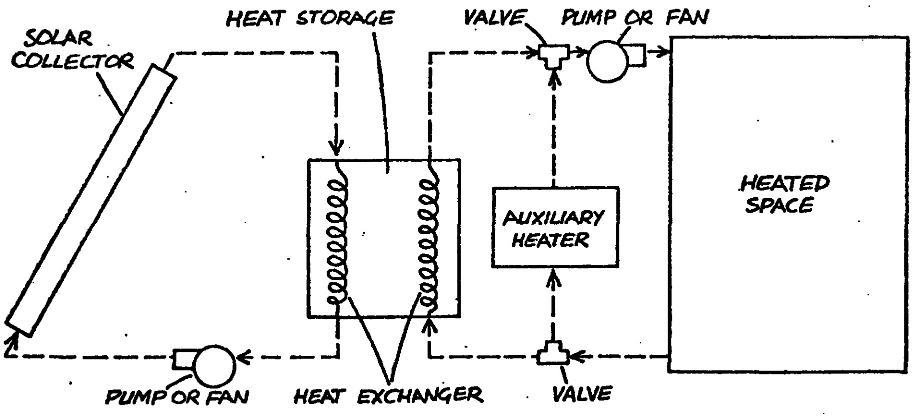
By contrast, the more complex active systems tend to have higher installment costs and require more maintenance, but they are also more versatile. With a storage system, the building temperature can be more easily regulated during both periods of high and low solar insolation. Excess heat can be stored during the day with controlled release during the night. Another advantage of collecting the heat in a storage tank is that it can then be used to heat water so as to drive a cooling system. Finally, active systems are more adaptable to existing buildings than passive systems which should be designed into a building before it is constructed. Only active systems offer the potential for widespread use of solar energy in Maine in the near future.

3.1.1 Solar Heating Systems

As outlined above, active systems typically include the following elements (Figure 3.2):

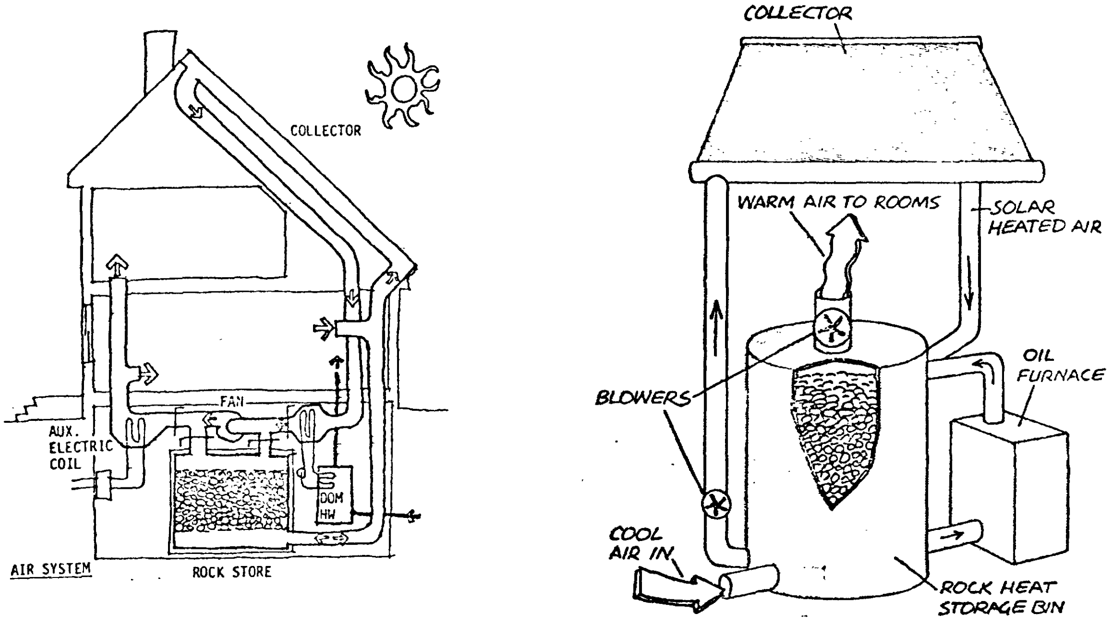
- collector
- storage
- plumbing and controls
- heat distribution system
- back-up system

Figure 3.3 illustrates solar heating systems using air as the heat transfer fluid. Figure 3.4 illustrates a solar heating system using water as the heat transfer fluid.



Solar Heating System
Figure 3.2

from (Anderson, 1976, p. 150)

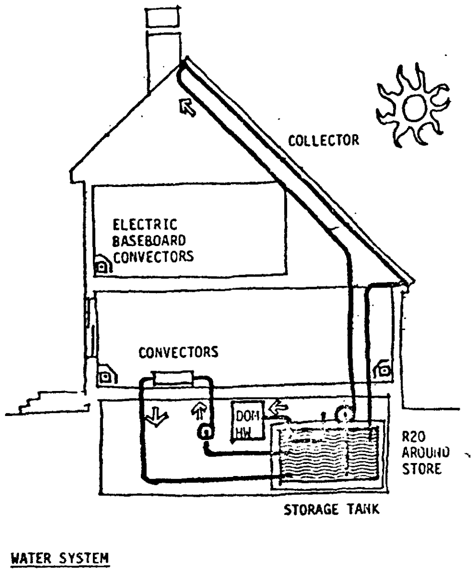


from (Massdesign, 1975, p. 6)

from (Anderson, 1976, p. 188)

Air Systems with Electrical and Oil Back-ups

Figure 3.3



Water System with Electrical Back-up

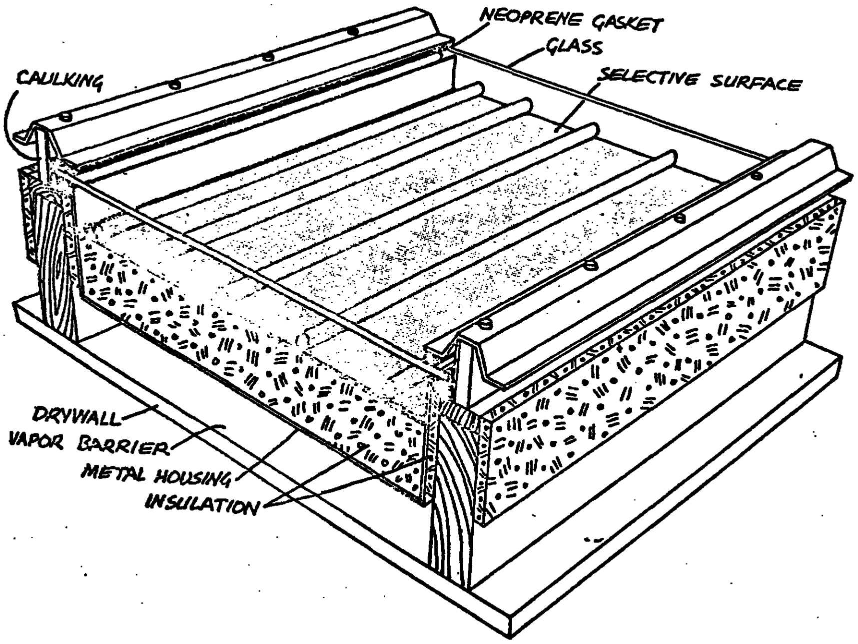
Figure 3.4

from (Massdesign, 1975, p. 6)

3.1.1.1 Solar Heat Collectors

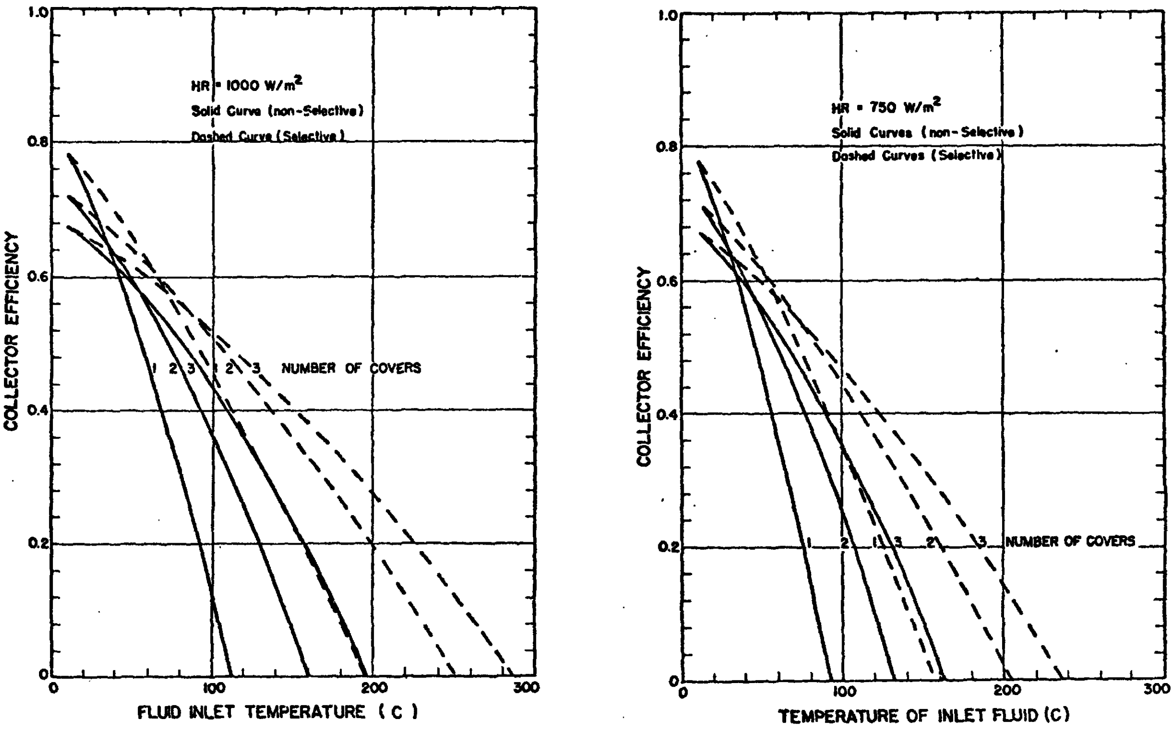
Flat plate collectors are the most common collectors used for home heating with solar energy. The basic components of a flat plate collector are: (1) an absorbing surface which is heated by the sun, (2) cover plates (glass or plastic) which allow the solar radiation through and which insulate against radiative and conductive heat losses from the absorbing surface to the air, (3) a circulating fluid (usually air or water) that transfers heat from the absorbing surface of the collector to the inside of the building, (4) insulating behind the absorbing surface to keep heat from being lost through the back of the collector.

Much research in solar energy has been on improving the performance of flat plate collectors. The research has focused on developing better plastics for the cover plates, designing methods of reducing convection losses from the collector, developing absorbing surfaces (known as selective surfaces) that convert more of the solar radiation into usable thermal energy, and finding new materials and methods of manufacturing to reduce the cost and complexity. A typical solar collector using water in pipes to transfer heat is illustrated in Figure 3.5. Figure 3.6 gives efficiencies for solar collectors with different characteristics. It should be remembered that any element added to improve efficiency (e.g., a second sheet of glass or a selective surface) will increase the cost of the collector.



Tube Water Solar Heat Collector with a Selective Surface
Figure 3.5

from (Anderson, 1976, p. 166)



Solar Collector Efficiency as a Function of Incident Radiation (HR), the Number of Coverplates, the Type of Absorbing Surface, and the Temperature of the Fluid as It Enters the Collector

Figure 3.6

from (Duffie, 1974, pp. 170-171).

Summaries of research on solar collectors done to date can be found in (Duffie & Beckman, 1974) and (Boer, v. II., 1976). Articles on current developments can be found in the periodical, Solar Energy.

3.1.1.2 Storage Systems

Storage systems are used in solar heating systems to maintain a reliable adequate energy supply in the face of diurnal and weather related fluctuations in insolation. The two most common storage materials, chosen for availability and low cost, are water and rocks.

In a water system heated water is stored in a well-insulated tank. Water passes from the solar collector directly into the tank or into a heat exchanger that is used to keep the collector fluid separated from the storage water. In a rock system hot air returning from the collector is blown over the rocks to heat them. To retrieve the energy cool air is blown over the hot rocks and is heated by them (see Figure 3.3).

Large volumes of water and rocks are required to store the thermal energy. Research is being done to find other materials which can retain as much heat as water or rocks but in a smaller volume.

The most promising materials are eutectic salts, but there are problems with loss of performance over time. (Duffie & Beckman, 1974, p. 232) The abundance, low cost, and desirable heat properties of water and rocks make them the best presently available storage media for small systems.

3.1.1.3 Auxiliary Equipment

Solar heating systems require a back-up heating system for those days when there is insufficient insolation and stored energy to meet the heating demand. Whether the collectors use air or water will determine whether water or rock storage, pumps or fans, and pipes or ducts are used. To some extent the auxiliary heater will be determined by the collector type too. If the system is being installed on an existing structure (retrofitting), then the existing heating system may influence the choice of the type of collector. A building with a hot water heating system would be more likely to use water collectors. In retrofitting, the existing heating system normally becomes the back-up for the solar heating system.

Other components of a solar heating system which are not shown in Figure 3.2 are the controls. Controls are required so that the storage system and the back-up heating system are used at the proper times to maintain the desired temperature. Controls are also required to turn the pump or fan off when the collector fluid temperature is too low. If cold fluid continued to circulate, the heat from the storage system would be transferred to the collector where it would be lost to the outside. In some climates, controls or additives are required to keep liquid systems from freezing in the collector. One method for preventive freezing is to drain, manually or automatically, the fluid from the collector whenever there is not enough insolation to collect heat. In some systems, antifreeze is added to the water. Additives are also used to prevent corrosion. Care must be taken that no additive leaks into the domestic water system.

3.1.2 Environmental Impacts of Solar Heating

The environmental effects of solar heat collectors for space and water heating are believed to be slight. The collectors absorb energy that might otherwise be naturally reflected back into the atmosphere. However, the proportion is not considered to be great enough to cause harm. (CEQ, 1975, p. 11-12). Contrasted with other heating systems which rely on combustion of fossil fuels or nculear energy (electricity) the net effect of solar heat utilization is beneficial, i.e., not producing air or water pollution.

The structure of the collector and light reflected from it might be considered local nuisances, but with proper design they should not present problems. Problems could also arise from large-scale use of antifreeze and anticorrosive additives if these chemicals were routinely discharged into sewage disposal systems during maintenance procedures. Secondary environmental effects of solar heating may result from the manufacturing of the panels, but since all materials used are currently in wide production, the incremental effects are likely to be negligible.

3.2 Industrial Process Heat

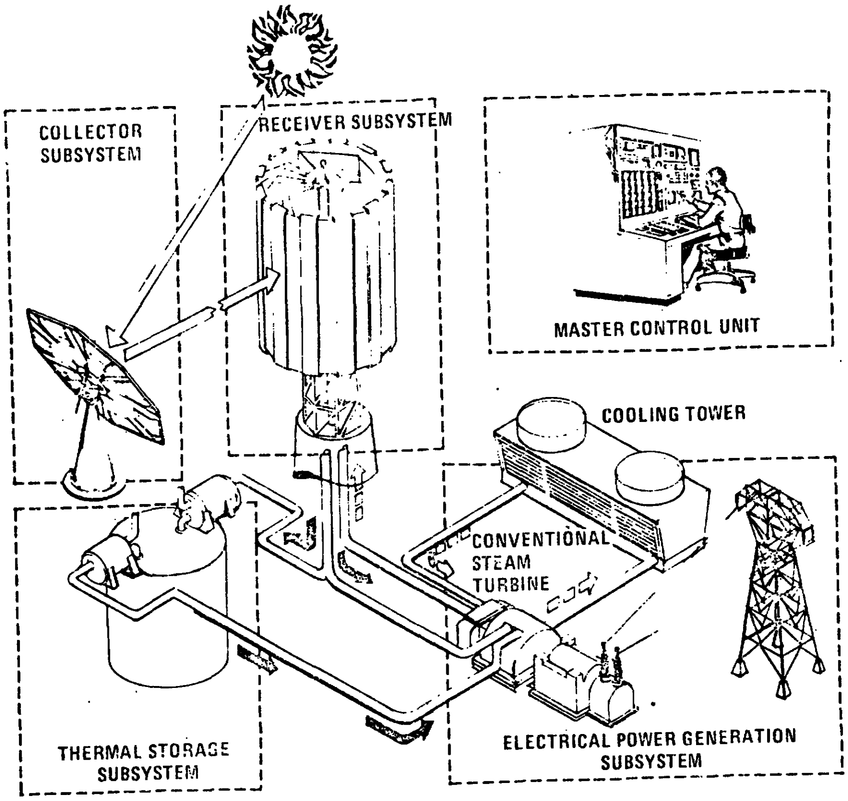
Many industrial processes use high-temperature steam that is produced by burning fossil fuel or occasionally by using electric resistive heaters. It is not possible to produce high-temperature steam with the flat plate collectors described above; however, if a focusing device is used, temperatures up to 800°C can be achieved (Grimmer, 1976, pp. 351-374). Since industrial processes vary greatly, solar derived process heat may be invaluable for one and useful for another (Figure 3.1). Virtually no experience exists with using solar energy for process heat.

3.3 Central Station Thermal Electrical Generation

A standard method for producing electricity is to use fossil or nuclear fuel to create steam to drive a turbine which turns an electric generator. Solar energy can be substituted for the fossil or nuclear fuel for the production of high-temperature steam. High temperatures can be achieved by using focusing and/or tracking systems as described in Section 2.

Several types of solar thermal-electric systems have been proposed, but only one appears to be receiving serious attention for development at present. The central receiver solar-thermal system consists of an array of mirrors that reflect the solar radiation onto a single thermal receiver, mounted on a central tower. The radiation heats a fluid in the central receiver which is used to drive a turbine. Figure 3.7 is an illustration of a central receiver system. The receiver system has five basic subsystems performing the following functions:

1) Concentration and transport of solar radiation
2) Absorption and conversion of solar energy into thermal energy
3) Storage of thermal energy
4) Generation of electric power
5) Control of system components

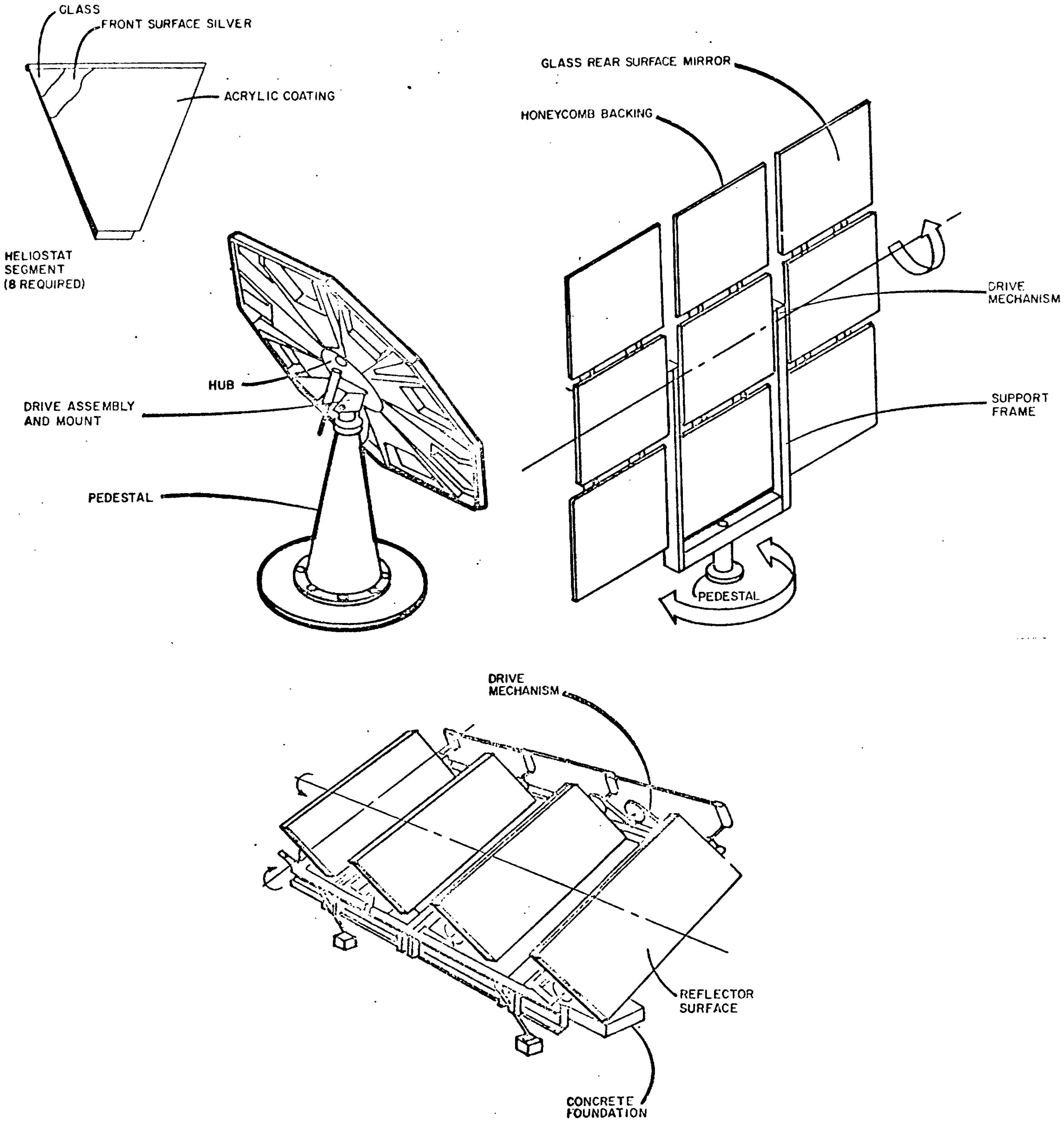


Central Receiver Concept
Figure 3.7

from (Gervais, 1976, p. 326)

3.3.1 Collector Subsystem

The collector subsystem consists of an array of mirrors which are used to focus the solar radiation onto the central receiver. As the sun moves across the sky, the mirrors follow its path so that the sunlight on the entire array area is always focused on the boiler. The mirrors and their associated components are commonly referred to as heliostats (Figure 3.8).



Heliostat Designs
Figure 3.8

from (Stone & Webster, 1976)

For areas with a high radiation flux, e.g., the U.S. Southwest, approximately one square kilometer (Van-Hull, 1976a, p. 31) of land would be required for the heliostat array to produce 100 megawatts of electricity (MWe). In the Northeast the required area would roughly double because the solar insolation is half as intense as in the Southwest (see Figure 2.4).

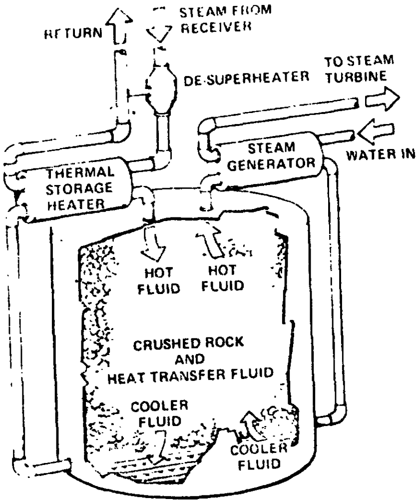
3.3.2 Central Receiver

The central receiver is located on a tower and is the focus for the reflected solar radiation. The concentrated solar energy heats a working fluid that circulates through the receiver, changing it to a gaseous state. (Normally, the working fluid is water, which is heated to steam.) The hot gas is then either used to drive a turbine or its heat is stored for later use. Cooled fluid is circulated back to the central receiver and the process continues.

3.3.3 Thermal Storage Systems

Energy storage can provide a buffer for short-term fluctuations in insolation and can also provide a source of energy for time periods with little or no insolation. The storage system may be associated with a particular plant in which case it is called a dedicated storage system, or the storage may be available to all plants on the electric utility grid. This latter type of storage will be discussed in Section 3.4.1. Dedicated storage is more appropriate when thermal energy must be stored because it is impractical to transmit thermal energy over long distances.

The thermal storage subsystem can be split into three basic parts: the thermal charging loop, the heat extraction loop, and the thermal storage device. Several thermal storage devices that have been proposed for use are similar to those used in home heating systems except that they are designed on a much larger scale. For example, in one proposed design, excess thermal energy is transferred from the steam to a fluid. This hot fluid is then passed through crushed rocks thus heating them. To retrieve the stored energy, cool fluid is passed through the rocks, is heated, and in turn heats water to make steam. The steam can then be used to produce electricity (Figure 3.9).



Thermal Storage Subsystem
Figure 3.9

from (Gervais, 1976, p. 333)

Another proposed design used the latent heat of fusion of an eutectic salt to store thermal energy. The steam from the receiver heats a fluid which in turn melts the eutectic salts. In the heat extraction loop, thermal energy is transferred from the salts to the working fluid. In giving up energy, the salts become solid again. The working fluid can then be used to heat water into steam. Development work is continuing on eutectic salts because their heat storage performance deteriorates as they go through the cycles of heating and cooling. (Duffie & Beckman, 1974, p. 232).

One problem with storage is that inevitably energy is lost in the process of charging and discharging. The precise efficiency depends on many factors including the difference in temperature between the working fluid and the storage medium and the rate at which the unit is charged and discharged. A unit with an efficiency of 70% would be considered a good storage device. (Cooper & Pepper, 1976, p. 16) That is, for every ten units of energy sent to the storage device, seven units could be recovered as usable energy.

3.3.4 Generation of Electric Power

In contrast to the components discussed so far, this subsystem uses a well-developed technology. All the subsystems described above were required to produce thermal energy equivalent to that produced from burning fossil fuel. The thermal energy is used to drive a turbine, converting thermal energy into mechanical rotational energy which in turn is used to generate electricity.

Disposal of the rejected heat of solar thermal-electric power plants is as much of a problem as it is for fossil fuel plants. In conventional thermal/electric plants, for every BTU of electrical energy output, three BTU's of thermal energy must be input. Solar thermal plants will be a bit more inefficient, about four BTU's of thermal energy input will be required for every electrical BTU. The rejected heat is at too low a temperature to be used for electrical generation and must either be used for another purpose such as space heating or disposed of into the air or water. Because power plants tend to be isolated, frequently the only option is to dispose heat to the air or to a nearby body of water. The technology for doing this has been well developed by the electric power industry. The proposed designs for central thermal plants use dry cooling towers because the power plants are designed for the U.S. Southwest where water is scarce, but other technologies such as wet cooling towers might be more appropriate in other locations.

3.3.5 Control System Components

The principal control problems revolve around maintaining focus of the sun on the central receiver. Each heliostat must be continuously adjusted as a function of the sun's position in the sky. In addition, control decisions for power plant operation and storage utilization must be made. Sophisticated sensing and control components are currently available for these tasks.

3.3.6 U.S. Development Program

The U.S. Energy Research and Development Administration (ERDA), now the Department of Energy (DOE) has been funding development of the central station solar thermal electric plant concept. (See Reference ERDA 1976). Their program has the following major goals: development of a 5-MW solar test facility in New Mexico in 1977, design and construction of a pilot 10 MWe plant by 1980, and demonstration of a 100 MWe commercial plant by 1985. The basic elements of the proposed 10 MWe plant are illustrated in Figure 3.10.

The Sandia Laboratories, Livermore, California, are the technical managers of the project. There are four prime contractors involved in Phase I, the 10 MWe pilot plant. They are the Honeywell Corp., Martin-Marietta Aerospace Corp., McDonnell-Douglas Astronautics Co., and the Boeing Engineering and Construction Co. There are a number of subcontractors who work on components and subsystems.

The 5-year schedule for the development of the 10 MWe plant and the schedule for the development and construction of the 100 MWe plant are shown in Figure 3.11. The preliminary characteristics of the 10 MWe pilot plant are listed in Table 3.1.

Central receiver (tower) solar plants should operate best in the Southwest USA where the direct beam solar radiation is highest and there is clear dry, usually dust-free desert air. The highest probability of success of a development program should exist there. The DOE program is, therefore, initially centered around systems that will be constructed in the Southwest USA.

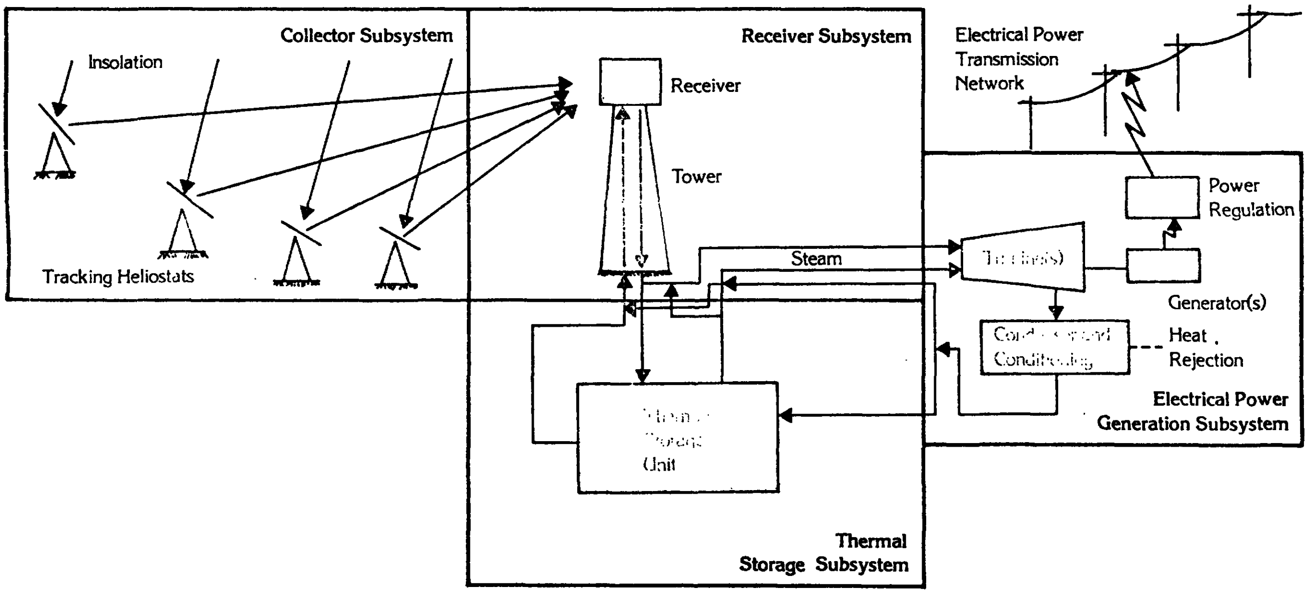


Figure 3.10

Central Receiver Solar Thermal Power System of Phase I ERDA (DOE) Program

Source: ERDA Div. of Solar Energy

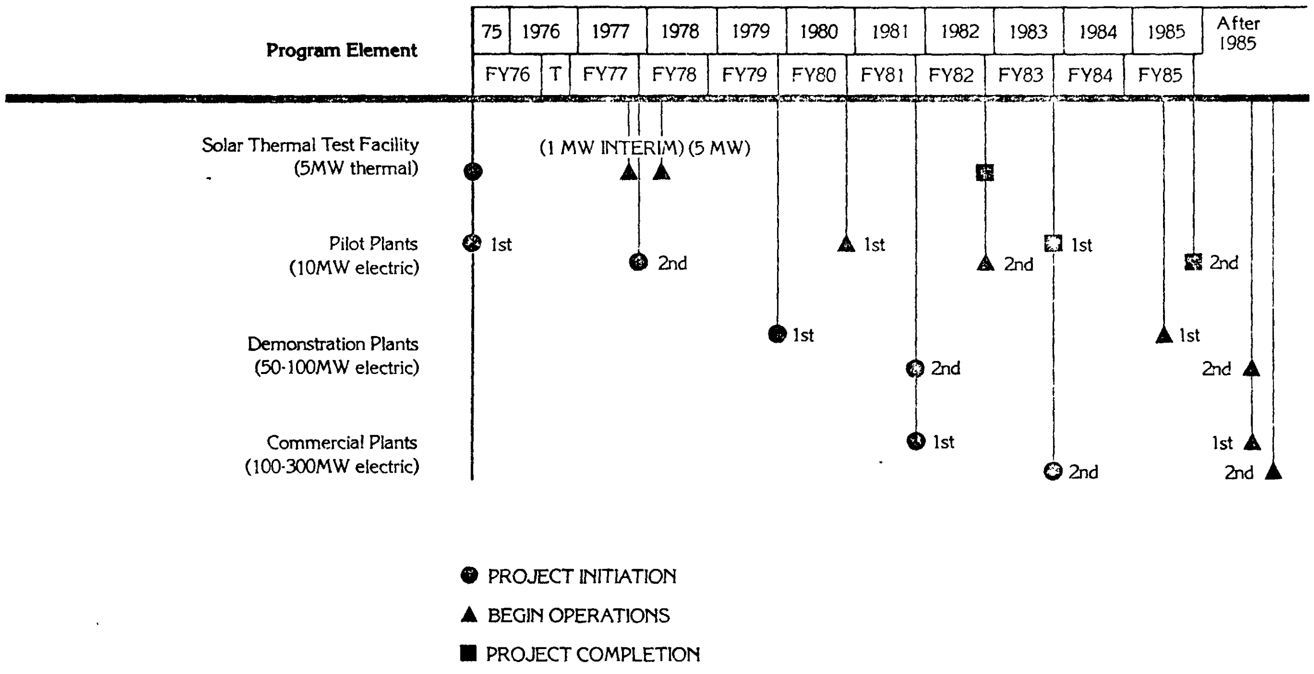


Figure 3.11

Central Receiver and Test Facility Projects-100MWe

Source: ERDA (DOE) Div. of Solar Energy

Table 3.1
Preliminary Characteristics of 10 MWe Solar Central Receiver Power Plant

	Boeing	Honeywell	Martin-Marietta	McDonnell-Douglas
Annual Energy (MW-hr)		4.3×10^4	3.4×10^4	3.6×10^4
Collector Subsystem				
Heliostat Construction	metallized plastic reflector; aluminum and steel frame	glass mirror; low profile steel frame, multifaceted, focused	glass mirror, steel frame, multifaceted, focused	glass mirror, steel frame, multifaceted, focused
Number of Heliostats	3146	2320	1718	2350
Reflective Surface per Heliostat	29 m^2	40 m^2	37.2 m^2	30.8 m^2
Total Area Reflective Surface	91,234 m^2	92,800 m^2	63,866 m^2	72,380 m^2
Field Size		308 m radius	565 m x 565 m	527 m x 527 m
Receiver Subsystem				
Receiver Type		vertical cavity	horizontal cavity	external absorber
Tower Height		146 m	137 m	101.4 m
Receiver Working Fluid		water/steam	water/steam	water/steam
Storage Subsystem				
Storage Mechanism		latent heat	sensible heat	sensible heat
Storage Media		salts	HITEC/hydrocarbon heat transfer fluid	rocks/hydrocarbon heat transfer fluid
Electrical Generation Subsystem				
Turbine Rating		15 MW	12.5 MW	15 MW
Turbine Fluid		steam	steam	steam

Source: ERDA (DOE) Div. of Solar Energy

3.3.7 Environmental Impacts of Central Station Thermal

Land usage and thermal pollution (due to waste heat) are the major known environmental impacts of central station solar thermal plants. Figure 3.12 compares the land use for a coal-fired and for a solar thermal plant. Over the lifetime of a plant the total land usage for a solar plant in the Southwest is less than for a coal-fired plant. Of course, the land disturbed by a fossil plant would not be entirely at the plant site in Maine. A central station solar plant located in the Southwest where water is scarce will have a problem disposing of waste heat. Fossil and nuclear plants using an equivalent thermal process have more freedom in site selection and can be located to alleviate waste heat disposal problems. Alternately, a central station solar plant located in New England would require twice as much land as in the Southwest, but water availability for waste heat disposal could be less of a problem.

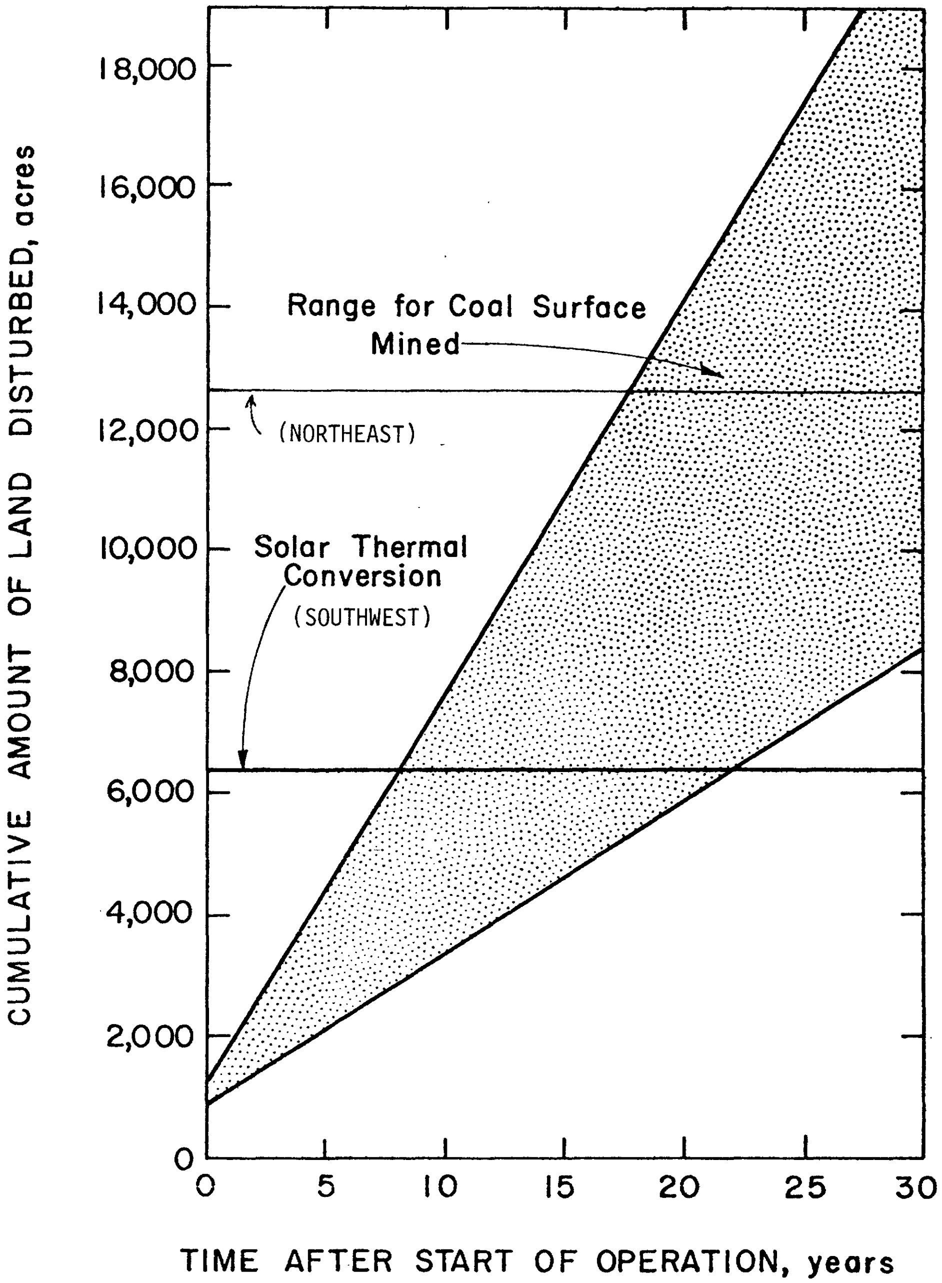
A major difference in environmental impacts is that solar thermal electrical generation produces no air pollutants or radioactive wastes. The absence of these pollutants and the availability of "free" energy are among the primary benefits of central station solar thermal.

3.4 Photovoltaic Generation

3.4.1 Photovoltaic Technology

The manufacturing technology for high quality photovoltaic cells for converting solar energy directly into electricity was developed by NASA for use on satellites and space travel. The application makes use of the photovoltaic effect which occurs when an electro-magnetic wave with sufficient energy (e.g., solar radiation) strikes an atom to break the bonds of an electron, separating it from the atom. This creates an imbalance of electrical charge. Eventually, the electron will recombine with an atom that is missing an electron. In order to use this effect to produce electricity, the freed electrons must be constrained to flow along a path to create a current before being able to recombine. To create a current, a crystal, such as silicon or gallium arsenide, is grown in thin layers. One layer of the crystal is made with a surplus of electrons by adding a small percentage of another element with more electrons per atom than the crystal material (n-type crystal). The other layer of the crystal is made with a deficit of electrons by adding an element with fewer electrons (p-type crystal). The layers are then arranged so that the solar radiation strikes the n-type crystal and electrons are freed. In order for the electrons to recombine with the "holes" in the p-type crystal, they must travel through an external circuit. The process is illustrated in Figure 3.13.

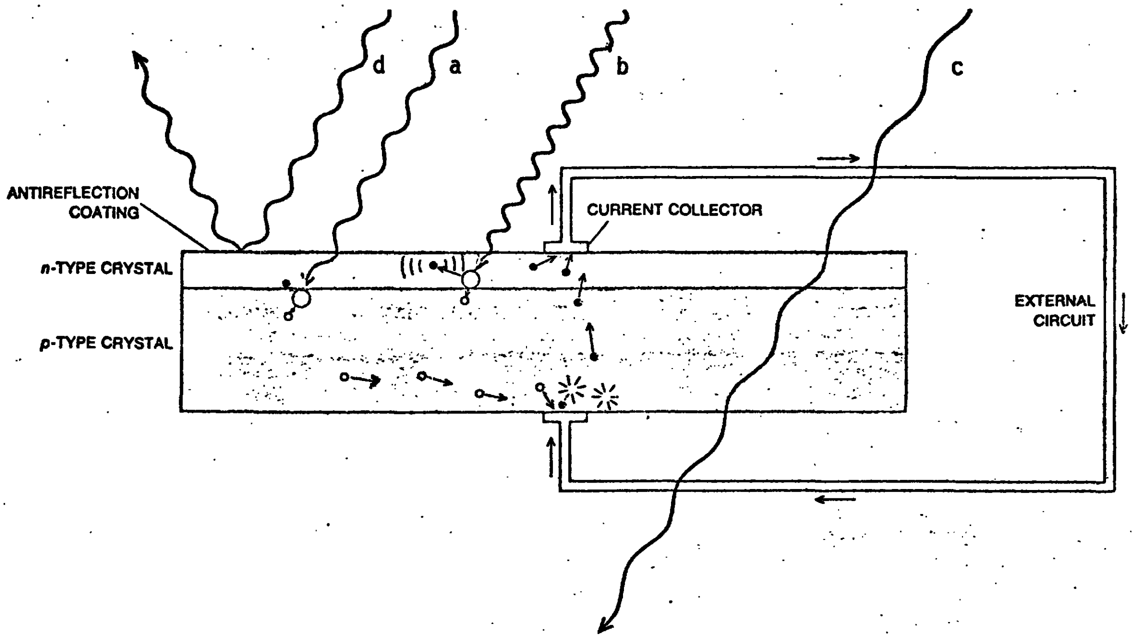
The photovoltaic cells have an intrinsically low efficiency, with respect to the total energy of solar insolation, because the electrons in a bound atom respond only at specific energy levels known as band gaps. If the incoming radiation has less energy than the band gap, then an electron cannot be freed. If the incoming wave has more energy than the band gap, an electron will become unbound but the excess energy will be converted into heat. Another source of loss is that the electric current collector covers part of the top layer thus blocking some of the sun's energy. The maximum theoretical efficiency of photovoltaic cells ranges from 22% to 24% depending on the band gap of the material. It is believed that photovoltaic cells with efficiencies of about 15% conversion of the energy in the incident solar radiation are realizable commercially. Table 3.2 gives the overall efficiency of a typical photovoltaic cell.



Comparison of Land Disturbed from Surface-Mined Coal and Solar Electric 1000 MWe Power Plant

Figure 3.12

modified from (CEQ, 1975, p. 11-13)



Silicon solar cell is a wafer of p-type silicon with a thin layer of n-type silicon on one side. When a photon of light with the appropriate amount of energy penetrates the cell near the junction of the two types of crystal and encounters a silicon atom (a), it dislodges one of the electrons, which leaves behind a hole. The energy required to promote the electron into the conduction band is known as the band gap. The electron thus promoted tends to migrate into the layer of n-type silicon, and the hole tends to migrate into the layer of p-type silicon. The electron then travels to a current collector on the front surface of the cell, generates an electric current in the external circuit and then reappears in the layer of p-type silicon, where it can recombine with waiting holes. If a photon with an amount of energy greater than the band gap strikes a silicon atom (b), it again gives rise to an electron-hole pair, and the excess energy is coverted into heat. A photon with an amount of energy smaller than the band gap will pass right through the cell (c), so that it gives up virtually no energy along the way. Moreover, some photons are reflected from the front surface of the cell even when it has an antireflection coating (d). Still other photons are lost because they are blocked from reaching the crystal by the current collectors that cover part of the front surface. All these losses mean that a real silicon cell cannot covert more than about 18 percent of the solar energy it receives into electrical energy (Chalmers, 1976, p. 38).

Silicon Solar Cell

Figure 3.13

from (Chalmers, 1976, p. 38)

3.4.2 Photovoltaic Cells

3.4.2.1 Status

Until 1973, photovoltaic cells production (cost was no object) was directed towards producing cells that could:

a) operate at efficiency levels approaching the theoretical limit of conversion
b) result in maximum reliability performance
c) function within the hostile environment of space (meteorites, radiation near absolute zero temperature on one side and high temperatures on the other, etc.)

Analysis of the cost effectiveness of any of the current solar photovoltaic systems, except limited military, space and special navigational and weather station applications, reveals that present day solar cells are far too expensive.

In addition, present manufacturing capacity is many orders of magnitude below what would be required if photovoltaic converters were to become economically viable.

3.4.2.2 U.S. Government Development Program

The U.S. Department of Energy has established a "National Photovoltaic Conversion Program" for which the overall objective is:

> "To develop low-cost reliable photovoltaic systems and to stimulate the creation of a viable industrial and commercial capability to produce and distribute these systems for widespread use in residential, commercial and governmental applications."

The ERDA (now the DOE) believes that it must continue to fund research so that the cost of cells can be reduced. One action is to "prime the pump" -- placing orders for cells in the expectation that manufacturing costs will decrease. Note that on Tables 3.3 and 3.4 it is hoped that by 1986 the total annual production of photovoltaic cells will be 500 MWe peak. This will be for all purposes, far from sufficient for a 600 MWe base-load power plant at Sears Island.

Photovoltaic Losses as a Percent of Incident Solar Energy	
Energy Lost in Low Energy Wavelengths	23%
Excess Energy in Absorbed Radiation	33%
Unrecovered Energy in the Band Gap	18%
Internal Losses	12%
Total Losses	86%
Useful Power Output 14%	

Table 3. 2

from (Daniels, 1964, p. 212)

Table 3.3 SUMMARY OF MAJOR COST GOALS - PHOTOVOLTAIC PROGRAM

OBJECTIVES / FISCAL YEAR	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	After
Market Goals											
Annual Production	0.4 MW_e		1.6 MW_e			30 MW_e		120 MW_e		500 MW_e	50 GW_e (by the year 2000)
System/Subsystem Costs											
Central Station											\$1100/kW_e (by 1990)* (rated)
Silicon Solar Arrays			\$5000/kW_e			\$2000/kW_e		\$1000/kW_e		\$500/kW_e	
Concentrating Arrays		\$2000/kW_e		\$1000/kW_e		\$500/kW_e				\$250/kW_e	
Thin Film Arrays										Feasibility \$100-300/kW_e	
Processes											
Silicon Production								2000 tons at \$10/kg			
Silicon Sheet Production										5 million m^2 at \$18/m^2	
Automated Solar Array Production										\$500/kW_e at 500 MW_e rate	

* System costs

Source: ERDA, Solar Energy Division, 1977.

A method for reducing the high cost of electricity produced by high cost photovoltaic cells is to reduce the number of cells required per unit of solar insolation collection area. This can be accomplished by collecting the solar energy incident on a larger area and focusing it on one or only a few photovoltaic cells. Tracking concentrators, such as lenses or parabolic reflectors (Figure 3.14), follow the sun across the sky concentrating the solar energy, incident on its large surface, to a very few cells located at their foci.

As long as the investment costs for tracking and concentration are less than the cost of the additional cells, required to cover the same collection area, for the same electrical energy output, tracking concentrators may be used. We must keep in mind that concentrators function with parallel, direct rays only. Non-tracking concentrators are designed to eliminate the need for tracking the sun (Figure 3.15). While not as efficient as parabolic concentrators, these devices are simpler to build and operate.

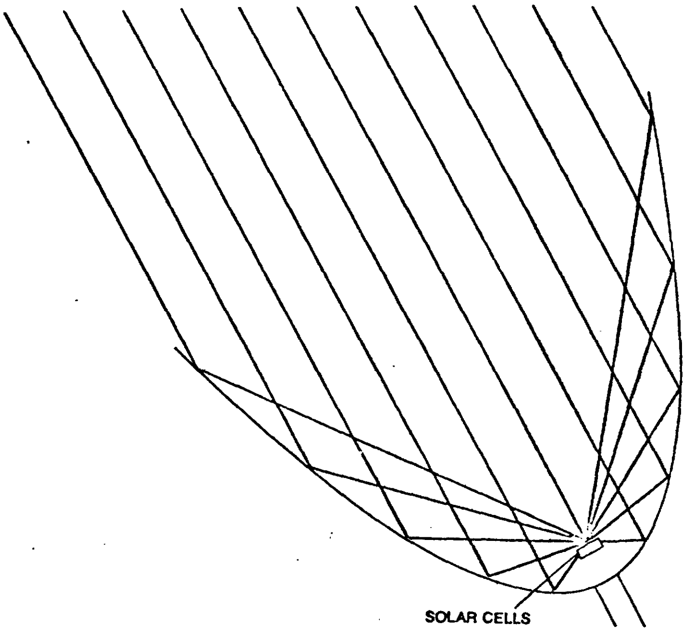


Figure 3.14
Parabolic Tracking Concentrator

from (Chalmers, 1976, p. 42)

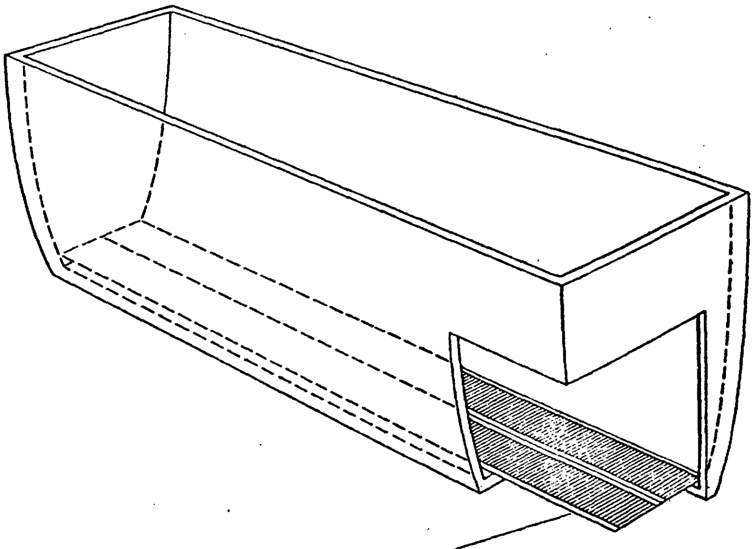


Figure 3.15
Winston Non-Tracking Concentrator

from (Chalmers, 1976, p. 93)

The system could be made more energy-efficient by utilization of some of the energy lost by non-conversion into electricity of the 80% incident solar energy by the cells. This energy is converted to heat and can damage the cells, particularly in concentrator systems, and further reduces operating efficiencies. Removal of excess heat both protects the cells and maintains efficiency. The most likely use of the relatively low-temperature heat thus removed by circulation of water or air beneath the cells is for space conditioning. In one proposed design, the absorbing surface of a flat plate collector is replaced by photovoltaic cells. This collector can produce from 60% to 90% of the thermal energy produced by an unmodified collector. In addition, it produces a supply of direct current electricity (Florschuetz, 1976, p. 89).

3.4.3 Residential and Commercial Uses

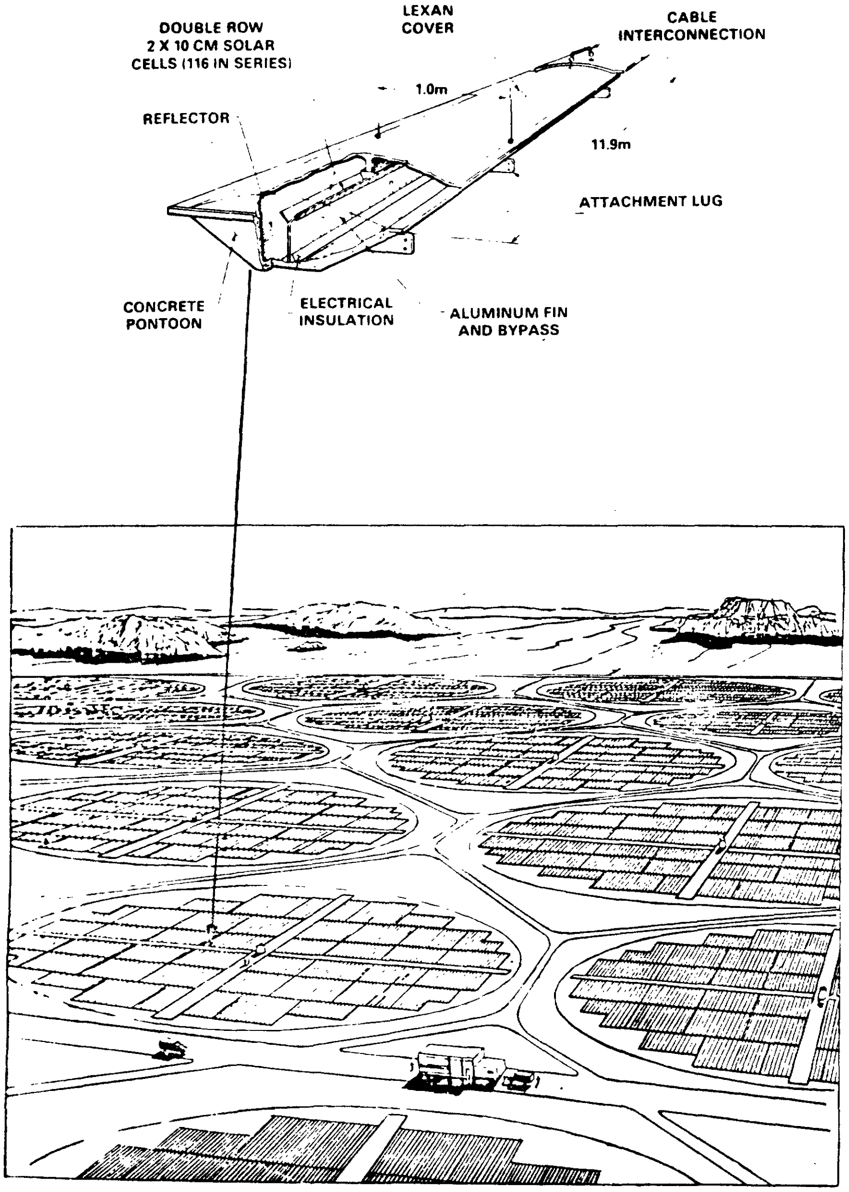
Most electrical equipment is designed to operate on alternating current. In general, only incandescent lighting and heating devices (e.g., toasters, stoves, hot water heaters) can operate satisfactorily on the direct current produced by photovoltaic cells. Such a segregation of use would probably discourage photovoltaics which produce only direct current.

Commercial power conditioning devices can be used to convert direct current electricity from solar cells to alternating current electricity which is compatible with that received from electric utilities. This would allow complete flexibility in the use of electricity from photovoltaic systems, but incurs added expense and inefficiencies for the conversion process. With inverter efficiencies of about 85% (Leonard 1975, p. 69), the total conversion efficiency from solar insolation to alternating current drops to around 10%.

Because electrical systems do not have the inertia of thermal systems, sudden drops in power input (e.g., a cloud passing in front of the sun) are reflected by equally sudden drops in power output. This unsatisfactory situation, and the problem of night time and cloudy day operation, require storage and back-up systems with short response times. Such storage systems are not yet commercially available. Back-up would have to be provided by the electric utility system.

3.4.4 Central Station Photovoltaic Generation

Central station photovoltaic generating plants are conceptually similar to the residential units just discussed. The scale is much larger but the basic components remain the same (Figure 3.16). Arrays of photovoltaic cells are electrically interconnected to provide direct current electricity to a centrally located inverter. The inverter produces alternating current electricity which can be fed into the utility transmission grid. Plant capacities on the order of 100 MWe are being studied (Leonard, 1975); no demonstration plants are currently in operation or under construction.



Solar Azimuth Tracker Power Plant

Figure 3.16

from (General Electric, 1977, p. 15)

Most conceptualizations of central station photovoltaic plants incorporate tracking concentrators to increase collection efficiencies. Because incident energies on the cells are increased, cooling systems are required.

For a 100 MWe plant in the U.S. Southwest, approximately two square kilometers of land are required (Leonard, 1975, p. 89). This is roughly twice the requirement for a 100 MWe solar thermal generating plant because of the conversion efficiency differences. Solar thermal is about 20% efficient (Hoover & Watt, 1975, p. 9) while, including inversion to alternating current, photovoltaic central station efficiencies are about 10% (Leonard, 1976, p. 69).

The problems of interruptions of solar insolation and storage for photovoltaic systems are similar for central station, residential and commercial size systems. Fast response (much faster than for a solar thermal plant) storage or back-up is required to keep the overall utility supply of electricity from dropping sharply if the sun goes behind a cloud. With a bulk power plant, however, the sudden power loss is now on the order of tens to hundreds of MW. A sudden demand for back-up power (or sudden restoration to full output of solar derived power when the sun shines again) presents serious problems for the utility generating system and transmission grid. Conventional generating units must be brought into operation quickly and power flows rerouted on the transmission system. This would be analogous to the sudden forced "outage" and "inage" of a conventional 100 MWe plant. If there were a number of solar stations, they could produce potentially serious problems of system stability and undesirable stress on the reserve generating units. Storage considerations may make centralized solar photovoltaic generation more acceptable than dispersed units (at each residence or commercial load center) if economies of scale make only large storage systems viable. Until rapid response, large-scale storage systems are developed for solar photovoltaic plants, this technology will not be as attractive as solar thermal power plants.

3.4.5 Environmental Effects of Photovoltaic Generation

The environmental impacts of the production of photovoltaic cells will depend both on the materials and the production method. Commercial production methods are currently the focus of research efforts and it is difficult to discuss their environmental effects. Except for the secondary effects of production, decentralized photovoltaics would have the same environmental impacts as the solar heat collectors described in Section 3.1.2. Central station photovoltaic systems will have potentially significant impacts in terms of land use and waste heat disposal.

3.4.6 Extra-terrestrial Photovoltaic Generation

The attenuation of solar energy by the atmosphere and weather, and the diurnal variation of power input are undesirable limitations on a solar collector on the earth's surface. It has been proposed that a photovoltaic collection system placed in earth orbit, beaming energy to the surface of the earth with microwaves, might eliminate most of these limitations at an acceptable cost (Glaser, 1977, p. 30).

Unlike the other technologies discussed here, this approach requires unproven, highly sophisticated equipment, construction methods and maintenance techniques. No private utility is likely ever to have the economic and technical resources to initiate this technology. At present it is only in a conceptual stage of development.

There may be potential health hazards associated with beaming microwaves from space since the concentration in the beam is well above the current acceptable limits for human exposure. There are also problems with the amount of land which would be covered by the microwave receiver and the water which would be required for cooling. Other environmental problems include the secondary effects of building and launching the rocket, satellite and solar cells, as well as building the receiving station.

4.0 ECONOMICS OF SOLAR ENERGY

4.1 Introduction

Estimating the economics of solar energy requires care in the establishment of the context in which solar energy applications are evaluated. In addition to the intended end-use purpose, considerable attention must be given to geographical location, local weather patterns, terrain topology, uncertainties of the outcome of existing and planned research and development programs and lack of understanding of social costs.

4.2 Cost Uncertainty

Solar thermal and photovoltaic plants have the large potential cost uncertainties characteristic of all technologies in the early stages of development. The necessary design of individual components of solar thermal stations requires no breakthroughs in the state of the art. Efforts here are primarily in determining the mechanical and thermal stress conditions of the overall system and designing components to accommodate these requirements.

The evaluation of the economics of terrestrial photovoltaic power plants has been based on the attainment of the 1985 DOE goal of $0.50/We peak for the photovoltaic modules (silicon cells). Higher cell costs will cause higher plant costs.

Orbital photovoltaic systems share the uncertainty of the silicon cell costs with the terrestrial photovoltaic plant, but in addition, have many other major subsystem cost and performance uncertainties (e.g., launch vehicles, space assembly techniques, manpower (astronauts), etc.).

Our discussions will address the economics of:

a) converting solar energy into heat, then into electricity at central bulk power stations

b) direct conversion of solar radiation into electricity by photovoltaic means at central stations, space satellites and dispersed locations

c) conversion of solar energy into heat energy for use as a substitute for electricity in providing hot water and space conditioning.

4.3 Central Station Solar Generation

The Department of Energy's research, development and demonstration program for solar energy, is the most extensive and complete available source of economic data on central station solar generation. Our analysis is based on their reported results. The program description contains the following opening statements.

> "The major issue in this program is the economics of the central receiver concept. Although no breakthroughs in the state of the art are required for the central receiver concept, the program demands considerable new technology. Initially, research and development will concentrate on developing low-cost components and on integrating these components into efficient systems. The three major subsystems that require development are energy storage, receivers and heliostats.

The cost of the mirror field, for example, represents approximately one-third to one-half of the total plant cost. Thus, further optimization and engineering to reduce component cost and to produce designs of higher efficiencies would have a major impact on the system cost.

In addition to establishing the direct economic costs, and developing the technology for the central receiver program, the preliminary design phase of the 10 MW pilot plant will also identify solar plant operational unknowns and indirect costs in order to assess the true cost of a central receiver power plant. These estimated costs will be closely monitored throughout the program to assess the appropriateness of further development of the central receiver concept."

4.3.1 Plant Characteristics

Nearly all studies conducted under DOE sponsorship have concluded that a solar thermal plant with a typical day performance profile similar to Figure 4.1 provides optimum economic performance. Note that a complex optimization of collection time, storage charging and discharging time and generation time is required. Such an optimization over random solar insolation, plant design parameters and plant operating schedules cannot be performed except in the context of a specific design study. No such study has been attempted here, but we have made some modifications to existing prototype design analyses to develop estimates of economics in Maine. Such estimates are reliable only in the sense of a lower bound on actual costs.

A photovoltaic central station plant has three characteristics which cause economics to differ with respect to a solar thermal unit.

a. Sunshine is converted directly to electricity at about 15% efficiency. There are further power conditioning losses which may reduce overall efficiency to about 10%.

b. Energy available for storage is in the form of electricity rather than heat, so different storage technologies (batteries, flywheels, etc.) are needed.

c. The design of a solar thermal plant is primarily one of sophisticated engineering. The major problem of photovoltaic plants is one of applied science -- "inventing" or "developing" a low-cost cell (growing proper crystalline structures), or finding unique ways to manufacture existing designs.

In Sections 2.2 and 2.3 we pointed out possible reasons for storage:

a) to behave as a buffer to sudden, brief changes in insolation

b) to provide energy for periods of cloudiness varying between 1/2 day and several consecutive days.

c) and, if desired, to permit base-load type of operation. The busbar electrical energy costs for internal storage schemes (heat in water, rock steel, salt eutectics, etc.) were compared with external storage schemes (pumped hydro, compressed air, flywheels, chemical batteries and superconducting magnets) for solar thermal power plants. (Manvi & Fujita, 1977). For a locality at which sunshine was available nearly every day (Southwestern USA) analysis revealed that the best case (least bus-bar cost) was for 6 hours of storage to provide power during the peak evening periods. Additional storage, to allow for performance as indicated in here and in b above, resulted in bus-bar costs far in excess of that from conventional plants.

The comparison is illustrated in Figure 4.2. The load factor L_2 is the ratio of hours of delivered energy in a 24 hour period. The differential energy costs for both internal and external energy storage in terms of ranges bounded by best and worst case combinations. While internal energy storage schemes (thermal) are more attractive than external energy storage schemes (batteries) the former are usable with solar thermal power generation and the latter are suitable for photovoltaic plants.

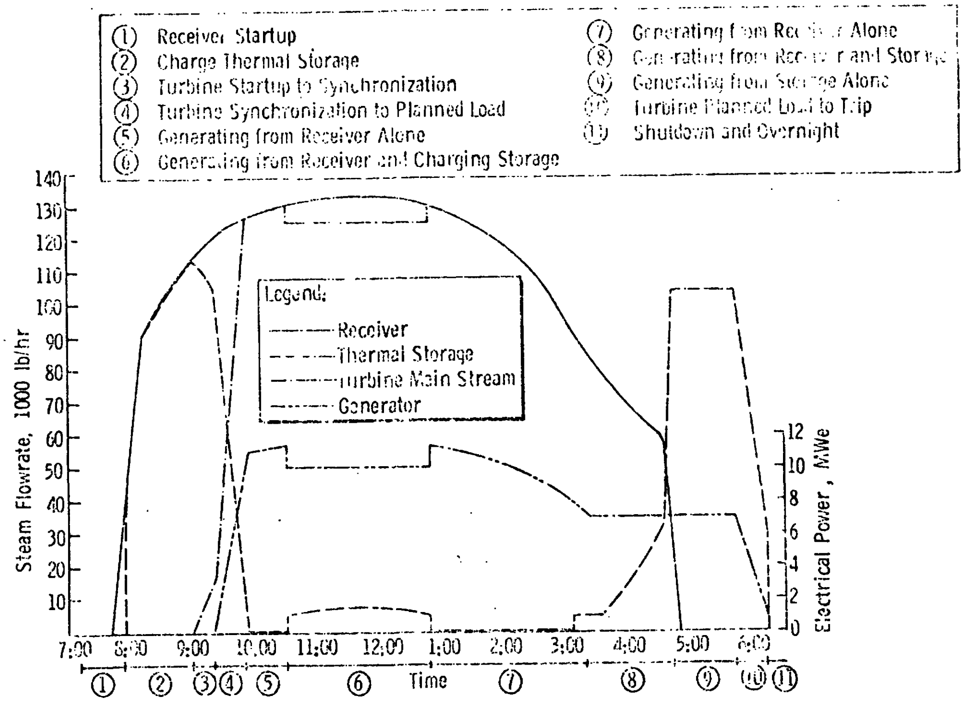


Figure 4.1

Typical Day Performance Profile

Source: ERDA

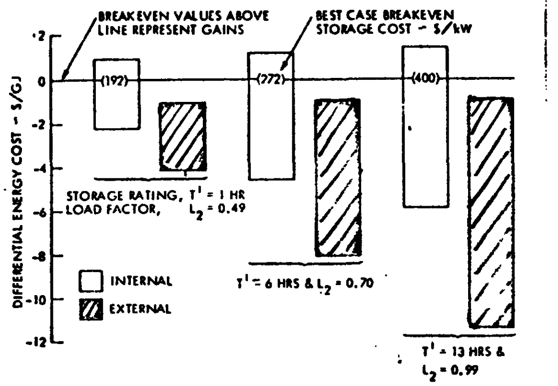


Figure 4.2 **Comparison of Internal and External Storage Systems**

4.3.2 Department of Energy Findings

DOE findings, as reported by the Jet Propulsion Laboratory (Caputo, 1976, Caputo 1979) indicate that solar thermal electric plants cannot economically compete on a "one-to-one" or "stand-alone" basis with fossil fuels or nuclear-fired facilities with base-load capability, even in the Southwest where insolation is more favorable than in Maine.

The requirement for storage not only causes a decrease in the overall conversion efficiency of the power plant but also results in a need for a much larger collector field. The field size must be adequate, not only to collect heat to operate the turbine during the day, but also to collect enough heat to allow the plant to operate from storage. Thus, the capital cost of power plants with energy storage will be considerably higher than equivalent sun-following plants.

The sensitivity of capital and energy cost to storage is shown in Figure 4.3. The cost of energy from conventional plants in the three categories, peaking, intermediate and base-load, as compared with solar thermal power plant designs for each of these categories is plotted in Figure 4.4. The difference in cost, at the "zone of closest approach" is shown to be on the order of 50 mills in 1975 or about 77 mills in 1986 dollars. This, too, is with 6 hours storage, sufficient only to act as a thermal buffer for short-time variations of insolation and to permit delivery of solar derived electricity for two hours beyond sunset.

In 1977 further results of economic studies were reported (Caputo, 1977). The results of a comparative assessment of orbital and terrestrial central power plants are shown in Table 4.1.

The terrestrial solar systems are both solar thermal using the central receiver approach with thermal storage, and solar photovoltaic using the silicon cell with battery storage. The 1985 DOE lowest cost photovoltaic goal of $1.50/peak watt is assumed to be achieved at 13% module efficiency. All terrestrial plants are either designed for or operated at an annual average load factor of 0.7, an assumed base-load factor.

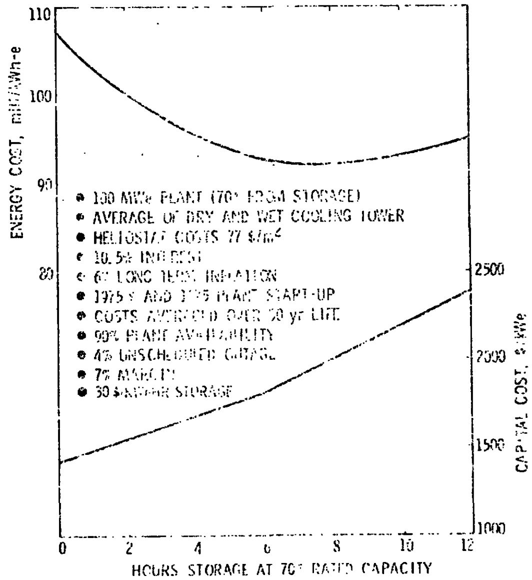


Figure 4.3
Solar Thermal Plant Costs vs Storage Capacity

Source: (Caputo, 1976)

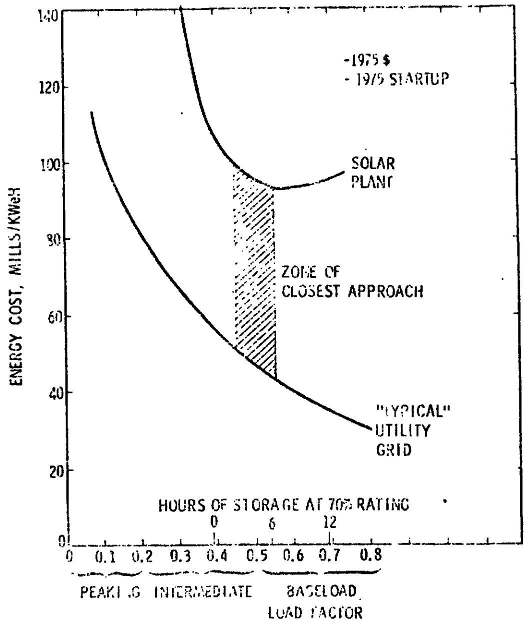


Figure 4.4
Energy Cost vs Load Factor
Source: (Caputo, 1976)

Table 4.1

Capital and Bus-bar Energy Costs
of Solar Central Power Stations

	Ground Solar		Orbital
Type of Plant	Thermal	Photo	Photovoltaic
Capital, \$/KWe	4573	7362[a]	7242[b]
Energy, mills/KWe hr[c]	113	162[a,d]	145[b,e]

3600 = 2950

Source: Derived from Caputo, 1977

---

[a] Average of pumped hydro and Redox battery storage
[b] 4-mil photovoltaics
[c] Energy costs based on 30-year life
[d] Hybrid operation at load factor = 0.864 to meet grid reliability with solar load factor = 0.70.
[e] Load factor = 0.864

The results are for a plant in the Southwest USA, having about 9 hours of solar storage capacity available at the plant, and providing extra back-up capacity (margin) in the form of gasified coal energy to make the individual ground solar plant with large solar grid penetration as reliable as conventional plants not subject to the sporadic unavailability of sunlight.

4.4 Dispersed Solar Water and Space Heating

There have been thousands of solar hot water and/or space heating installations made in the United States with about a thousand in all of New England. It is difficult to conduct an adequate economic study of what they cost. First, a large number were designed and installed by home owners. Hence, the reported costs vary between wide extremes and cannot be converted into numbers related to the cost of an open-market purchase, contractor-installed system. Those installed by contractors have been primarily in the Southwest USA, and the Southeast. Relatively few contractor-installed systems are located in the Northeast. Secondly, the economic performance data on "production type" facilities are sparse. Those contractors with whom we have spoken were reluctant to give us numbers -- "It is too early to have meaningful data ...."

It must be kept in mind that there are limits to the extent that "production line" techniques can reduce the cost of single- or limited multiple-family house solar systems. The existing structures number about 60 million nationally with an annual replacement of about one million. Retrofit is therefore the most significant opportunity. Retrofit, however, means almost custom-tailored designs and installation procedures.

For an individual user, the decision of whether or not to install a solar unit is much less complex than for a public utility, but the underlying principle is the same: a large capital investment is made in order to use a free source of power. An individual user does not have to be concerned with the effect that the unit will have on the electric utility system, but only whether it will save him or her money. There are, of course, other considerations beside cost involved in deciding to install a solar unit. Factors such as aesthetics, reliability and perceived risk also affect the decision.

To analyze the economic performance of decentralized solar units, the following minimum data are required:

- demand
- climatic conditions
- cost of back-up facility on site or required of the utilities
- back-up energy (fuel) cost and escalation rate
- capital cost and performance (lifetime, operation and maintenance expenses, taxes, etc.) of the solar unit
- discount rate

These data can be supplied in more or less detail depending on how one formulates the problem. Detailed demand and climatic data are required only in the design and sizing of the solar energy system. One could formulate the design problem to find the optimum collector area and storage volume for some stated objective. However, since the weather and the energy demand are intermittent and randomly variable, optimization is difficult. Most researchers have circumvented this problem by writing computer simulation programs to find the fraction of energy demand supplied by solar energy as a function of the collector and storage size. Once this function is know, the solar fraction can be optimized with respect to some other objective. The objective depends on who is looking at the problem. A home owner might want to minimize dollars spent. An electric utility might want to minimize the fossil and nuclear fuel consumed.

Almost all solar units have a back-up system which supplies energy when the solar unit cannot. Since a conventional unit would have been installed anyway, only fuel savings are attributable to the solar unit. For fuel costs, a conservative assumption is that costs will not increase at a rate greater than the overall inflation rate. A solar unit which is economically feasible under this assumption should be feasible under almost any additional assumptions since fuel costs are expected to continue to escalate at least at the general inflation rate.

To install a solar unit means that one is trading money which would be spent on fuel bills in the future for money spent on a solar unit today. For a home owner, the discount factor is frequently assumed to be the bank interest rate on loans or mortgages.

4.4.1 MITRE Corporation Study

The MITRE Corporation, under contract to ERDA, developed an economic analysis of solar water and space heating (MITRE, 1976). The scenario included solar heating and hot water systems for a new single-family residence compared with conventional systems.

In the report 13 cities which are representative of the expected variations in climate date and fuel costs in the United States were considered. Boston is the closest to Maine geographically, but climatically, Madison, Wisconsin is almost an exact match.

It is important to remember that in this study the analysis does not claim that installed collector costs <u>are</u> $\$10/ft^2$, $\$15/ft^2$, or $\$15/ft^2$. The study

a. asks, "Would solar energy be cost-effective <u>if</u> such solar collector costs were assumed to be possible?"

b. does not address the interaction of widespread solar hot water and space heating systems with utility rate structures

c. bases the analysis on newly constructed houses meeting the latest in insulation standards.

Table 4.2 summarizes the results which are related to the New England climate:

TABLE 4.2

SOURCE: An Economic Analysis of Solar Water & Space Heating; (MITRE, 1976)

METHOD: A computerized simulation model (FCHART) is used to find the fraction of the load provided by a solar unit as a function of the collector/storage size and the thermal load. Life cycle costs are minimized to find the optimum solar fraction. Collector costs are varied. Results are given for Boston, Mass. and Bismarck, N.D. Maine is similar to Bismarck in climate and to Boston in fuel costs.

All costs are in 1976 dollars.

BASE CASE ASSUMPTIONS:

LOCALITY		Bismarck	Boston
THERMAL LOAD (MBTU/YEAR)	SPACE HEATING	111.86	71.20
	HOT WATER	21.52	21.52
SOLAR FRACTION OF LOAD	SPACE HEATING	depends on fuel - see results	
	HOT WATER		
FIXED COSTS ($)	SPACE HEATING	-	
	HOT WATER		
*COLLECTOR COST ($/FT^2)	SPACE HEATING	$10	
	HOT WATER		
*STORAGE COST ($/FT^2)	SPACE HEATING	included in Collector cost	
	HOT WATER		
MAINTENANCE COST($/YEAR)	SPACE HEATING	2% of initial cost	
	HOT WATER		
RETROFIT COST ($)	SPACE HEATING		
	HOT WATER		
AUXILIARY POWER ($/YEAR)	SPACE HEATING		
	HOT WATER		
SYSTEM LIFETIME (years)	SPACE HEATING	20	
	HOT WATER		
BACKUP FUEL COST ($/MBTU)			
electricity		$8.24	$13.48
oil		$3.38	$3.20
gas		$1.12	$2.82
DISCOUNTING METHOD: 30-yr mortgage		8.5%	
ANNUAL COST INFLATION		6%	
ANNUAL FUEL COST ESCALATION		10%	
INCOME TAX BRACKET OF BUYER		30%	

*NOTE: THIS IS AN "IF" NUMBER: IF THE SOLAR COLLECTOR COULD BE BOUGHT AND INSTALLED AT THIS COST.

(continued on following page)

TABLE 4.2 Cont.

RESULTS:

CONVENTIONAL SYSTEM USED FOR COMPARISON	COLLECTION SIZE (FT^2)	ANNUAL INCIDENT SOLAR ENERGY (MBTU)	LOAD BY SOLAR (%)	SOLAR SAVINGS ($)	Years to Positive Savings	Years to Payback
BISMARCK						
10 $\$/\text{FT}^2$ Scenario	NOTE: This is an "if" number.					
Hot Water:						
Electric	153.	90.77	92.0	8439	1	7
Oil	136.	80.52	89.6	4433	1	9
Gas	68.	39.55	63.1	421	7	19
Hot Water & Heat:						
Electric	1140.	675.93	84.2	43423	1	8
Heat Pump	814.	482.56	74.7	19543	1	11
Oil	828.	481.48	72.0	19589	1	11
Gas	*	*	*	*	*	*
BOSTON						
10 $\$/\text{FT}^2$ Scenario	NOTE: This is an "if" number.					
Hot Water:						
Electric	255.	115.38	94.1	14179	1	6
Oil	154.	68.86	77.7	2940	2	12
Gas	136.	61.08	73.7	2336	2	13
Hot Water & Heat:						
Electric	1144.	517.91	77.8	36233	1	9
Heat Pump	651	294.83	61.7	12249	2	13
Oil	492	220.53	51.6	7571	3	14
Gas	423	189.23	47.6	5803	4	14

*Insufficient Solar Load, i.e., less than 40 percent Hot Water & Heat or less than 50 percent Hot Water only.

NOTE: <u>IF</u> THE SOLAR COLLECTOR COULD BE BOUGHT AND INSTALLED AT THIS COST.

1. It was assumed that the life of the solar system would be 20 years.
2. The percent of solar load (how much of the heat or hot water requirement) which could be met as a function of collector in a given city was calculated.
3. Using the results of thermal analysis, an alternative procedure was used to select a collector area which minimized the life-cycle costs.

The procedure compared variations of the "fuel" cost of a conventional heating system (electricity, oil, or gas), the cost of solar equipment as a function of collector area, energy that could be supplied for heating by sunshine as a function of a collector size and time of year, and plotted the variation in life cycle costs, years to positive savings and years to payback.

The results of the MITRE study can be interpreted as follows: If a solar system could be installed for $10 per square foot, and an electrical back-up heating system was already installed and we considered only the cost of the electricity required for back-up (to supply energy not furnished by the sun) then the optimum hot water/heat and hot water solar energy systems would

a. have 255/1144 square feet of collector
b. receive 115.38/517.91 MBTU
c. deliver 94.1/77.8 percent of the requirements
d. result in a lifetime (20-year) savings of 14,719/36,233 dollars
e. begin to pay back the investment in 1/1 years
f. complete pay back in 6/9 years

Table 4.3

SOLAR ECONOMICS FOR 20 $/FT INSTALLED COST

DEFINITION: A SYSTEM IS ECONOMIC IF POSITIVE SAVINGS OCCUR IN 5 YEARS OR LESS OR PAYBACK OCCURS IN 15 YEARS OR LESS. Y = YES

	HOT WATER			HOT WATER AND HEAT			
	ELECT.	OIL	GAS	ELECT.	H.P.	OIL	GAS
ATLANTA	Y			Y			
BISMARCK	Y			Y			
BOSTON	Y			Y			
CHARLESTON	Y			Y			
COLUMBIA	Y			Y			
DALLAS/FT. WORTH	Y			Y			
GRAND JUNCTION	Y	Y		Y			
LOS ANGELES	Y			Y			
MADISON	Y			Y			
MIAMI	Y			Y			
NEW YORK CITY	Y			Y			
SEATTLE							
WASHINGTON, D.C.	Y			Y			

Source: (MITRE, 1976)

Table 4.4 ECONOMICS OF SOLAR HOT WATER AND HEAT SOLAR ECONOMICS FOR 15 $/FT^2 INSTALLED COST

DEFINITION: A SYSTEM IS ECONOMIC IF POSITIVE SAVINGS OCCUR IN 5 YEARS OR LESS <u>OR</u> PAYBACK OCCURS IN 15 YEARS OR LESS. Y = YES.

	HOT WATER			HOT WATER AND HEAT			
	ELECT.	OIL	GAS	ELECT.	H.P.	OIL	GAS
ATLANTA	Y			Y		Y	
BISMARCK	Y	Y		Y	Y	Y	
BOSTON	Y			Y			
CHARLESTON	Y	Y		Y		Y	
COLUMBIA	Y			Y			
DALLAS/FT. WORTH	Y			Y			
GRAND JUNCTION	Y	Y		Y	Y	Y	
LOS ANGELES	Y	Y		Y	Y	Y	
MADISON	Y			Y	Y		
MIAMI	Y	Y		Y		Y	
NEW YORK CITY	Y			Y	Y		
SEATTLE							
WASHINGTON, D.C.	Y			Y			

Source: (MITRE, 1976)

Table 4.5 ECONOMICS OF SOLAR HOT WATER AND HEAT SOLAR ECONOMICS FOR 10 $/FT^2 INSTALLED COST IN 1980

DEFINITION: A SYSTEM IS ECONOMIC IF POSITIVE SAVINGS OCCUR IN 5 YEARS OR LESS <u>OR</u> PAYBACK OCCURS IN 15 YEARS OR LESS. Y = YES.

	HOT WATER			HOT WATER AND HEAT			
	ELECT.	OIL	GAS	ELECT.	H.P.	OIL	GAS
ATLANTA	Y	Y	Y	Y	Y	Y	Y
BISMARCK	Y	Y		Y	Y	Y	
BOSTON	Y	Y	Y	Y	Y	Y	Y
CHARLESTON	Y	Y		Y	Y	Y	
COLUMBIA	Y	Y		Y	Y	Y	
DALLAS/FT.WORTH	Y	Y	Y	Y	Y	Y	Y
GRAND JUNCTION	Y	Y	Y	Y	Y	Y	Y
LOS ANGELES	Y	Y	Y	Y	Y	Y	Y
MADISON	Y	Y		Y	Y	Y	
MIAMI	Y	Y	Y	Y	Y	Y	Y
NEW YORK	Y	Y	Y	Y	Y	Y	Y
SEATTLE		Y				Y	Y
WASHINGTON, D.C.	Y	Y	Y	Y	Y	Y	Y

Source: MITRE, 1976

Table 4.6

SOURCE: The Economics of Solar Home Heating, (Shuze <u>et.al</u>., 1976)

METHOD: A computerized simulation model (LASL) is used to find the fraction of the load provided by the solar unit as a function of the collector/storage size and thermal load. The present value of heating costs is minimized to find the optimum solar fraction. The solar costs are annualized at a real (deflated) interest rate to arrive at the annualized cost per unit of energy. This cost is compared to an annualized cost for conventional fuels which is computed using an econometric model. A solar unit is considered to be feasible in the first year that solar costs are less than fuel costs.

All costs are for 1976 given in 1974 dollars.

BASE CASE ASSUMPTIONS:

LOCALITY		Maine
THERMAL LOAD(MBTU/YEAR)	SPACE HEATING	112.67
	HOT WATER	15
SOLAR FRACTION OF LOAD	SPACE HEATING	?
	HOT WATER	
FIXED COSTS ($)	SPACE HEATING	$1100
	HOT WATER	$ 300
*COLLECTOR COST ($FT^2)	SPACE HEATING	$9.50
	HOT WATER	$11.00
STORAGE COST ($/FT^2)	SPACE HEATING	included in collector cost
	HOT WATER	
MAINTENANCE COST($/YEAR	SPACE HEATING	.75% of initial cost
	HOT WATER	1.0% of initial cost
RETROFIT COST ($)	SPACE HEATING	$3400
	HOT WATER	-
AUXILIARY POWER($/YEAR)	SPACE HEATING	-
	HOT WATER	-
SYSTEM LIFETIME (years)	SPACE HEATING	30
	HOT WATER	20

BACKUP FUEL COST ($/MBTU)
annualized for 30 yrs from 1976 - space heating - $5.86
annualized for 20 yrs from 1976 - hot water - $5.92

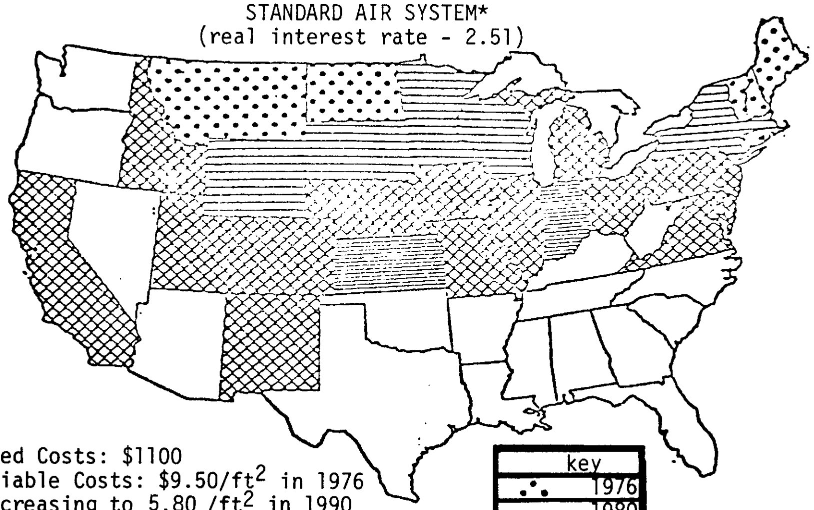
DISCOUNTING METHOD:	real interest rate 2.5%	
ANNUAL COST INFLATION		-
ANNUAL FUEL COST ESCALATION		econometric model
INCOME TAX BRACKET OF BUYER		NA

*THIS IS AN "IF" NUMBER: <u>IF</u> THE SOLAR COLLECTOR <u>COULD</u> BE INSTALLED AT THIS COST.

key	
●●	1976
═	1980
✕✕	1985
≡	1990

RESULTS: Map 2

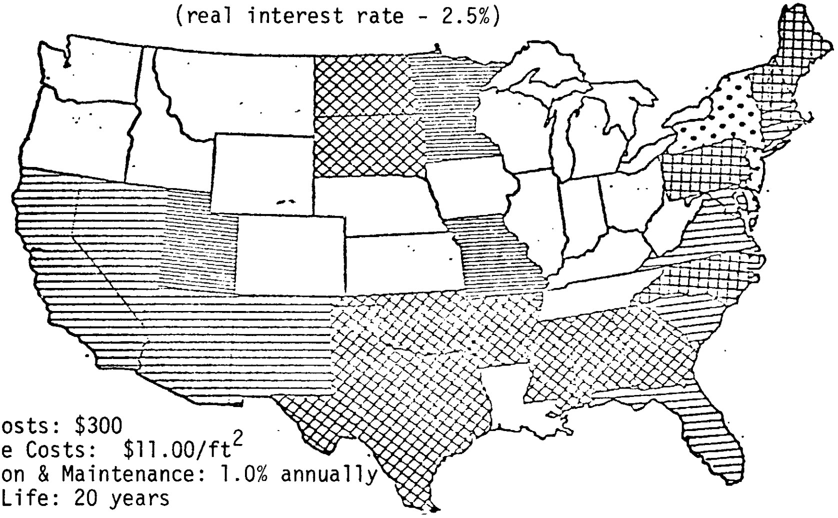
SOLAR FEASIBILITY - RESIDENTIAL SPACE HEATING
STANDARD AIR SYSTEM*
(real interest rate - 2.51)



*Fixed Costs: $1100
Variable Costs: $9.50/ft^2 in 1976
decreasing to 5.80 /ft^2 in 1990
Operation & Maintenance: 0.75% annually
System Life: 30 years

key	
●●	1976
═	1980
✕✕	1985
≡	1990

Map 5
SOLAR FEASIBILITY - DOMESTIC HOT WATER
(real interest rate - 2.5%)



*Fixed Costs: $300
Variable Costs: $11.00/ft^2
Operation & Maintenance: 1.0% annually
System Life: 20 years

Table 4.7

SOURCE: Solar Heating in the United States, (Duffie, Beckman & Decker, 1976)

METHOD: A computerized simulation model (FCHART) is used to find the fraction of the load provided by a solar unit as a function of the collector/storage size and the thermal load. Annual savings are maximized to find the optimal solar fraction and hence the collector/storage size. Fuel and collector costs are varied to test the sensitivity of the solution. A breakeven fuel cost is computed.

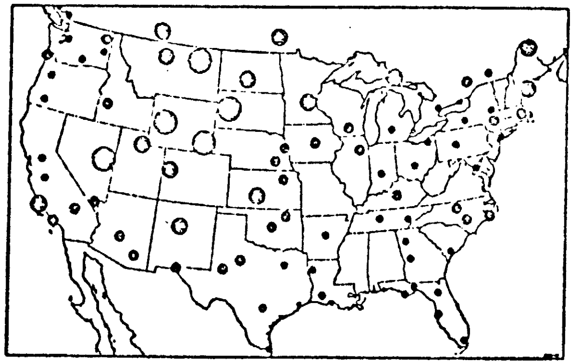
All costs are in 1976 dollars.

BASE CASE ASSUMPTIONS

LOCALITY		Portland, Maine
THERMAL LOAD (MBTU/YEAR)	SPACE HEATING HOT WATER	?
SOLAR FRACTION OF LOAD	SPACE HEATING HOT WATER	58%
FIXED COSTS ($)	SPACE HEATING HOT WATER	$1000
*COLLECTOR COST ($/FT^2)	SPACE HEATING HOT WATER	$10.22
STORAGE COST ($/FT^2)	SPACE HEATING HOT WATER	$1.39
MAINTENANCE COST ($/YEAR)	SPACE HEATING HOT WATER	
RETROFIT COST ($)	SPACE HEATING HOT WATER	NA
AUXILIARY POWER ($/YEAR)	SPACE HEATING HOT WATER	-
SYSTEM LIFETIME (years)	SPACE HEATING HOT WATER	
BACKUP FUEL COST ($/MBTU)		$10.55
DISCOUNTING METHOD: annualized fixed charge		10%
ANNUAL COST INFLATION		-
ANNUAL FUEL COST ESCALATION		NA
INCOME TAX BRACKET OF BUYER		

RESULTS: For Portland, Maine, annual savings are $218 under base case assumptions.
Breakeven fuel cost is $7.06/MBTU

The following map summarizes the savings for the U.S. under base case assumptions. Large to small dots represent annual savings greater than $300, $200-$300, $100-$200, and $0-$100.



*NOTE: THIS IS AN "IF" NUMBER: IF THE SOLAR COLLECTOR COULD BE BOUGHT AND INSTALLED AT THIS COST.

Table 4.8

SOURCE: The Use of Solar Energy for Space Heating and Hot Water, (Massachusetts Energy Policy Office, 1976)

METHOD: A solar fraction of 50% of the load is assumed. The breakeven cost for solar collectors is found using projections of future fuel prices.

BASE CASE ASSUMPTIONS:

LOCALITY		Massachusetts
THERMAL LOAD(MBTU/YEAR)	SPACE HEATING	80
	HOT WATER	20
SOLAR FRACTION OF LOAD	SPACE HEATING	50%
	HOT WATER	
FIXED COSTS ($)	SPACE HEATING	NA
	HOT WATER	
COLLECTOR COST ($/FT^2)	SPACE HEATING	NA
	HOT WATER	
STORAGE COST ($/FT^2)	SPACE HEATING	NA
	HOT WATER	
MAINTENANCE COST ($/YEAR)	SPACE HEATING	$.05/ft^2
	HOT WATER	
RETROFIT COST ($)	SPACE HEATING	NA
	HOT WATER	
AUXILIARY POWER ($/YEAR)	SPACE HEATING	-
	HOT WATER	-
SYSTEM LIFETIME (years)	SPACE HEATING	20 years
	HOT WATER	
BACKUP FUEL COST($/MBTU)		
electricity		$9.60
oil		$4.00
gas		$4.00
DISCOUNTING METHOD: annualized fixed charge -		10%
ANNUAL COST INFLATION		
ANNUAL FUEL COST EXCALATION		4%
INCOME TAX BRACKET OF BUYER		25%

RESULTS: Breakeven solar costs per square ft. of collector

	Gas/oil	Electricity
Space heating	$6.28	$15.89
Hot water	$13.14	$32.34
Heat & Hot Water	$8.00	$20.00

The results of analysis are summarized in a more general way in the Tables. In Table 4.3 it is indicated that if a solar hot water and heating system could be installed today at a cost of $20 per square foot, solar energy could be cost-competitive with electricity in Madison, Wisconsin (Augusta, Maine). In Table 4.4 it is indicated that if a solar system could be installed today at a cost of $15/ft^2 it could be cost-competitive with a heat pump system. In Table 4.4 it is indicated that if a solar system could be installed today for $10/ft^2, it could be cost-competitive with oil.

4.4.2 Other Studies of Dispersed Solar Heating Economics

Several other theoretical studies have been performed to assess the feasibility of solar space and water heating for New England or for all of the United States. Tables 4.6 through 4.8 summarize the assumptions and results from four studies. Comparison is difficult due to differing assumptions and accounting methods, but solar space and water heating appear to be economically feasible in New England now or in the near future if collector costs were from $10 to $20 per square foot. (The breakeven collector cost is frequently assumed to include the cost of the storage system, the controls and installation. The breakeven collector cost is found by dividing the total system cost by the number of square feet of collector.) One study (Table 4.8) showed a breakeven cost over $30 per square foot for hot water systems.

4.4.3 Experimental Studies

There are two current, but quite different solar studies going on in New England, one by Converse, the other by the New England Electric Company.

4.4.3.1 A. O. Converse

A. O. Converse, at Dartmouth University, has been monitoring solar heated buildings in Northern New England (Table 4.9). Although none of the systems has been studied long enough to make any definite statements, the systems appear to provide a smaller fraction of demand than most studies find to be optimal, and cost more than most studies assume. The higher cost can be partially explained since each of the installed systems is a prototype and is not being mass-produced. The collector costs are certainly within the range of economic attractiveness addressed above.

Table 4.9

House #	1	2	3
Solar fraction	38.2%	40.6%	41%
Collection area ft^2	700	400	806.7
Total cost	$10,400	$7,500	$12,500
Collector cost $/ft^2	$14.86	$18.75	$15.50
Storage type	water	water	rock
Backup	electric	oil with electric heat pump	electric

Data on Solar Homes in New England

Source: (Converse, 1975-76)

Even so the systems: (a) are not like the ones the general public is expected to buy;
(b) were not manufactured and installed in conformance to the government and industry standards that are anticipated;
(c) were not installed under the trade union imposed conditions which are anticipated.

4.4.3.2 New England Electric Study

Another experimental study is currently being performed by the New England Electric Company. They have installed 100 solar hot water heaters in Massachusetts, New Hampshire and Rhode Island. Bids were taken from companies who could supply a solar hot water heater with 50 square feet of collector area. Bids for systems costing over $3000 were rejected. Performance varies greatly, with the highest solar fraction provided being 40% and the lowest 4%. Since the collectors were not sized by the amount of demand that would be placed on them, the solar fraction may not rperesent the true performance of a collector. The average cost of the systems is $40 per square foot of installed collector area (Table 4.10). This number represents a situation in which "normal" procurement and installation procedures would have taken place, and is quite high compared to the values assumed in most studies and those given in Table 4.8 from other installed systems.

A detailed analysis of the experiment is being performed by the A. D. Little Co. This report, when it is published, may give more insight into causes of the high costs and poor performances of many of these systems. An interview with a representative of New England Electric is reproduced in Section 5.

TABLE 4.10

Granite State Electric Company
Massachusetts Electric Company
The Narragansett Electric Company

Solar Water Heating Project

FACT SHEET

1. Program: Nation's first major residential solar water heating test project (joint customer/company participation)
2. Number of Customers: 100
3. Estimated Cost of Project to Company: $400,000
4. Cost to Each Participating Customer: $200
5. Length of Program: two years
6. Estimated Cost of Equipment (complete systems): $1,000 to $1,600
7. Actual Cost of Equipment and Installation (by bids): $1,400 to $2,900
8. Average Installed Cost of Complete System: $2,000
9. Customer Selection Criteria:
   a) single family house
   b) southern exposure free of shading trees, shrubs, plants and buildings
   c) sufficient space for solar collector (outside) and storage tank, piping/duct connections
   d) agree to contribute $200 toward cost of testing a solar-electric water heating system
   e) agree to one to two year test period
   f) customer can keep system after test period at no additional cost
10. Time Schedule: Solicit customer participation in mid-September 1975. Have 100 solar systems installed by the end of Summer 1976.
11. Program Objectives:
    a) determine efficiency of solar energy for heating water
    b) determine if solar water heating systems can conserve energy
    c) determine how much money such systems can save customers
    d) determine if saving can offset cost of equipment
    e) determine if solar systems will allow company to reduce costly electric generation projects
    f) determine which is best currently available solar water heating method
    g) determine if solar energy is a viable energy source for New England
12. Manufacturers of Solar Equipment Participating in Project
    a) 20 manufacturers
    b) 18 different collectors
13. Types of Systems Being Tested
    a) liquid closed loop: 73
    b) direct water: 23
    c) air: 4

4.4.3.3 The U.S. Department of Housing and Urban Development

The U.S. Department of Housing and Urban Development has awarded a number of third-cycle award grants intended to promote the use of solar energy. There were three grants for Maine, two for single-family dwellings and one for a 91-unit multiple-family medium-rise apartment house.

We were unable, at the time of this writing, to obtain information about the proportion of energy the installations are anticipated to save. Neither could it be determined whether the grant represented all or a portion of the actual cost.

4.4.4 Summary (Dispersed Solar Energy Heating and Hot Water)

The economic studies which were reviewed indicate that for New England solar energy systems for hot water and/or space heating will

a. require collector costs in the range of $10 to $20 per square foot installed and including storage, depending on the fuel used as back-up

b. require conventional back-up systems (not necessarily electric).

There are insufficient experimental performance data to justify general conclusions about installation, operation and maintenance costs. There is potential for dispersed solar heating on hot water systems to supplement electricity use in Maine, since the experimental economics appear close to the desirable range. However, it is presently impossible to estimate the extent of solar's contribution to a reduction of electricity demand. Furthermore, when the back-up is electricity, the requirement for plant capacity remains.

4.5 Photovoltaic Power Systems for On-site Residential Applications

Photovoltaic systems may be installed on individual dwellings to provide all or part of the electricity needs of the occupants. It is technically feasible to do so but, again, at present prices of photovoltaic cells it is far from being cost effective.

Kirpich et al. (Kirpich, 1976) have examined the performance and conducted a cost analysis of residential photovoltaic systems for on-site residential applications. The results of their cost analysis yielded the preferred system sizing (solar cell area and battery capacity) associated with the minimum cost of energy supplied. For a 30-year levelized cost of $0.05/kwhr the maximum allowable capital cost of solar arrays varied from $0.90/peak watt in Phoenix, Arizona down to $0.45/peak watt in Cleveland, Ohio for the case of the no-energy storage system.

The DOE schedule for reduction of the cost of solar cells, Table 3.4 and Table 3.5, shows that the situation as visualized by Kirpich would not exist until after 1985. There would be an additional period of several years before the total U.S. production capability would permit the number of installations made in Maine to reach the level where there would be significant "capacity credit" to merit reduction in size or elimination of the need for the Sears Island station.

4.6 Solar Energy with a Heat Pump

A solar thermal energy collector system in combination with a heat pump can be used effectively in certain parts of the U.S. Investigations conducted at the University of Pennsylvania, however, do not necessarily apply to Maine because the period during which the ambient temperature causes heat pump efficiency (COP, coefficient of performance) to fall below acceptable levels starts earlier in the heating season and extends further into spring.

Where the winter climates are severe, heat pump systems require appreciable amounts of supplemental electrical resistance heat (other sources are too capital intensive) that offset energy savings achieved through the amplifying effect of the heat pump system. Extensive use of the supplemental heaters also causes poorer demand and load factors for the electric utilities.

The Department of Energy is supporting research and development efforts for improved heat pump design and solar energy/heat pump systems. It is too early to speculate about the cost effectiveness of installations in Maine but the developments should be followed closely.

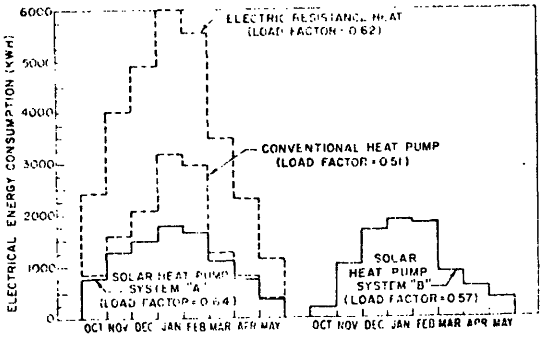


FIG.4.5 HEATING SYSTEM POWER CONSUMPTION 1500 FT^2 PHILADELPHIA RESIDENCE WINTER SEASON 1972-1973

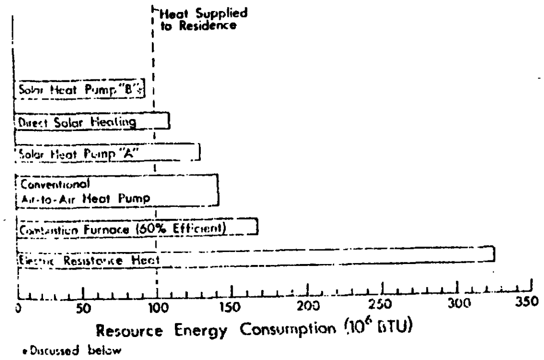
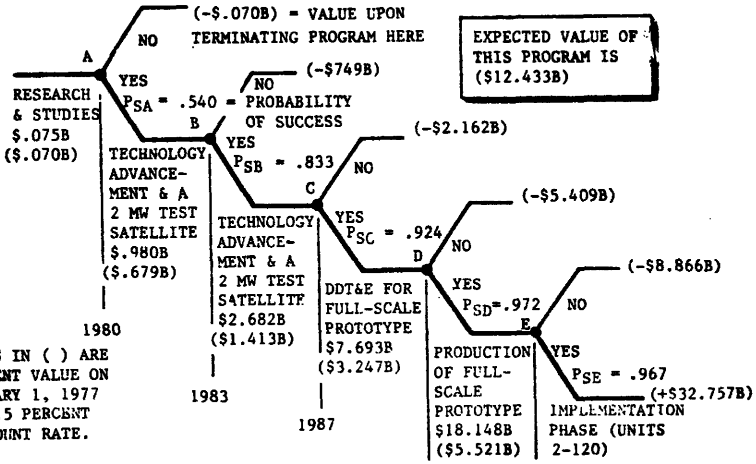


FIG. 4.6 COMPARISON OF RESOURCE ENERGY CONSUMPTION FOR VARIOUS HEATING SYSTEMS IN A 1500 FT^2 PHILADELPHIA RESIDENCE OVER 1972-1973 HEATING SEASON

4.7 Space Solar Power Stations

A study of the economics of space power system design and development, summarized in Figure 4.7, illustrates the length of time and the expenditure in dollars before a full-scale prototype might be available (Hazelrigg, 1977). Clearly a space solar power station is not a candidate for consideration to meet the anticipated electric power requirements of Maine in 1985.



NOTE: COSTS IN ( ) ARE PRESENT VALUE ON JANUARY 1, 1977 AT 7.5 PERCENT DISCOUNT RATE.

FIG. 4.7 An SSPS Development Program Decision Tree

5.0 SOME INSTITUTIONAL BARRIERS AND CONSTRAINTS

5.1 General

The interplay between technical, economic, social and legal factors will be of concern to the users and implementers of solar energy systems. The more serious institutional impediments are:

a. the state regulatory procedures and rate-setting policy.
b. state and local building safety and housing codes.
c. zoning (land use) regulations.

There are a number of strategies for dealing with the discontinuous availability of solar energy and the resulting need for back-up:

1. Limit solar energy use to those few applications where constant energy is not required.
2. Provide storage at the collection/usage sites.
3. Maintain sufficient conventional reserve capacity in the utility system to supply back-up in sunless periods.
4. Develop rate structures or control schemes to discourage the use of the utility system for back-up.

Figure 5.1

Tests show solar heaters not so hot

By Jerry Ackerman
Globe Staff

'Standards have to be written, and they have to be written quickly . . . and the industry has to police itself. . . .'

—John F. Meeker

The nation's first large-scale test of home solar hot water systems, being conducted in 99 New England homes, is finding costs ranging well above what had been expected — and energy savings often far below what the units' manufacturers had claimed.

Much of the discrepancy can be attributed to the infancy of the solar-heat industry, which has a handful of larger manufacturers and a plethora of one-man and two-man shops. Some have likened the situation to the early days of the automobile industry, when many models were one-of-a-kind because they did not stand up under use.

The results offer a caveat to homeowners considering taking part in a Federal grant program, announced earlier this week, which will provide $400 to homeowners to install their own sun-powered hot water systems to reduce reliance on electricity as a fuel.

The US Department of Housing and Urban Development (HUD) program is distributing $10 million in 10 states with high electric rates. All the New England states except Maine are included. Massachusetts officials say details for awarding the grants — 1375 will be given in the state — won't be known until April 14.

Meanwhile, the test sponsored by the New England Electric System in homes in Massachusetts, New Hampshire and Rhode Island so far has shown these results:

—Costs of the systems, installed, have averaged $2000, compared with estimates of from $1000 to $1700 made by solar system manufacturers before the test started. The cheapest system installed cost $1400; the most expensive, $2900.

—While manufacturers claimed energy savings of 40 to 60 percent, only two of 20 systems being used are reaching the 40-percent level and about 10 a 30-percent level. Average savings are 20-25 percent. One system saved only 4 percent.

—These numbers suggest that rather than paying for themselves in 6 to 7 years as initial estimates said, solar hot water systems won't recover their costs in reduced electric bills for 18 to 20 years. This estimate takes into account interest payments buyers would make on loans to buy and install the systems.

These were the principal points in a report presented to an energy task force of the Federal Regional Council, a body of representatives of principal Federal agency offices in New England, by John F. Meeker, supervisor of the experiment which New England Electric initiated in late 1975.

Meeker said in a telephone interview that in general, the most successful installations have been those by manufacturers that followed up on the operational efficiency of their units.

The lack of standards both in manufacture of equipment and methods of installation, as well as lack of training for plumbers and heating technicians who install and service the units, also have been problems, Meeker said.

"Standards have to be written, and they have to be written quickly," he said, "and the industry has to police itself and get rid of quick-buck artists."

The experiment was begun by New England Electric in part to determine the potential of solar systems to reduce electric utilities' need to maintain extra generating capacity to serve customers during peak-use hours.

Participants — selected for the suitability of their homes to make best use of solar power — paid $200 each toward the equipment. The company paid the remainder of the costs and is monitoring results throughout the test period, which will end in 1979.

Interview from The Boston Globe, April 2, 1977

The first two alternatives achieve independence from the utility system, but at a high cost in terms of versatility or investment in storage and increased collector area. The latter two alternatives bring into play the state regulatory process since large amounts of solar capacity will affect the design and operation of the conventional utility system. This is true both for effective capacity wherein solar units serve existing demand, and for true capacity, wherein solar units supply power to the grid. Some of the problems which are not yet resolved are:

- whether a utility is required to provide back-up on demand
- whether a utility must accept a reverse flow of power into its grid
- allocation of safety and interconnection costs for solar units connected to the utility grid
- establishment of incentives for central station solar plant construction
- establishment of rates for back-up sales and reverse flow purchases, including the issue of allocating investment costs for utility generation required to meet back-up demand

These problems, which apply to other intermittent energy sources as well, could have a significant impact on the economic incentives for solar units. Their solutions are a matter of public policy; there are no "right" technical answers.

Dispersed solar units must comply with local codes for safety and housing. Depending on the nature of these codes, most of which presently have no explicit provisions for solar construction or equipment, the use of solar energy will be enhanced or discouraged. While present experimental experience reflects in some sense the constraints of existing codes, this regulatory area will probably become more complex with an unpredictable impact on costs of installation and maintenance.

Zoning and land use regulations are another area which will have an unpredictable effect on the introduction of solar units. Solar units are considered unsightly by some and this may generate opposition to their widespread installation. Another problem, concerning sun rights, i.e., a property owner's right to receive some share of sunlight, is not yet an issue. As more units are built, possibly being shaded by neighboring vegetation or other solar devices, regulations will be developed in this area with further unpredictable economic effects.

5.2 Solar Energy/Electrical Utilities

The advantages of solar energy's long-term and widespread availability and pollution-free utilization are offset by its short-term fluctuations and the capital investment needed to provide for its collection and storage in a form acceptable for use during unilluminated hours. It is the requirement for additional collection and storage, so as to provide continuous capability, that pushes the economics "out of sight", and encourages consideration of the feasibility of utilizing solar energy systems that do not have "base-load" capability. The problem is, of course, that the demand for heat, hot water, or electricity does not follow, minute by minute, the availability of sunshine. Under present regulations utilities would have to have installed generation capacity to absorb 100% of the solar supplied load. There are, however, times when utilities have more capability than the current demand, and generation capacity is idle.

There have been a number of schemes proposed for solar systems to be integrated into the conventional electrical supply configuration so as to permit the use of solar energy without economic penalty or inconvenience. The simplest would be one in which a fuel-intensive conventional generation facility would save fuel by reducing output when solar energy is available. The advantages would be reduced fuel imports and environmental impact.

Another would be prearranged agreements with customers so that if a portion of their energy requirements were supplied by solar energy, the customers would not ask the utilities to supply that which could not be supplied by solar energy unless the utility had unused capacity.

Still another arrangement would be for customers to include at their facilities storage that could be "charged" during periods that the utility had excess capacity. The amount of that storage, as compared with that required for a solar "stand-alone" situation, would be much less and, in addition, the collection devices need not be oversized to provide energy for storage.

The basic problem is that arrangements of the sort described above represent a departure from the current electrical utility regulatory body/customer system that has developed over a period of at least 75 years. Our social and economic habits would have to be disturbed in a major way. Whether the public is willing to accept such changes for the sake of solar energy is uncertain.

Table 5.1 gives a rough optimisitic estimate of potential impacts of solar devices on demand in Maine in January 1985. It is not a definite analysis of capacity credit, but merely an exercise intended to give some feeling for the range of numbers involved. An optimistic estimate that 50% of the space and water heating customers have solar units by 1985 is used. Assuming that the units provide a 25% monthly solar fraction (approximately full daytime operation for 2 out of 3 days), a reduced energy demand is computed. The energy demand can be translated into a capacity demand if one assumes that the heating load occurs uniformly throughout the day. The additional assumption is made that solar units use, by means of special metering and control systems, only off-peak energy for back-up. With these most optimistic assumptions, solar heating could replace approximately 65 MW of capacity in 1985.

TABLE 5.1

HYPOTHETICAL IMPACT OF RESIDENTIAL SOLAR HEATING ON CAPACITY REQUIREMENTS IN MAINE IN 1986

	space heating only	water heating only	space and water heating
Percent of residential energy use for each heating class in 1985 (1)	42%	8%	39%
MWh consumed in 1985$^{(2),(3)}$	1,342,725	213,131	1,039,013
Percent of annual energy consumed in January (1)	16%	10%	15%
MWh consumed in January 1985	214,833	21,313	155,851
MWh consumed by solar users$^{(4)}$	107,417	10,657	77,926
Percent of energy provided per user by solar units in January (5)	25%	25%	25%
MWh supplied by solar units	26,854	2,664	19,482
Equivalent MW capacity assuming uniform demand (6)	36	3	26

Total capacity replaced by solar heating: 131 MW

Assumptions:

(1) Data from the Central Maine Power Company's submission to the Maine Public Utilities Commission, June 1977

(2) 43,634 x 10^9 BTU are consumed to produce electricity for residential use in 1985 in Maine (Page, 1976, Table 3.0)

(3) BTUs are converted to MWh of end use electricity with an efficiency of 25%:

Boiler efficiency	68%
Thermal efficiency of turbine	40%
Generator efficiency	96%
Transmission efficiency	96%

Overall efficiency = 68 x 40 x 96 x 96 = 25%

from (Thirring, 1958, p. 24)

(4) Assuming 50% of customers in each class have solar units

(5) Assuming each solar unit provides 50% of the household heating demand in January

(6) Assuming the electricity demand for heating is constant throughout the day and storage is used to prevent need for back-up power. If the demand is not constant, then a greater installed solar capacity is required to meet the demand.

6.0 CONCLUSIONS

1. Space and water heating are currently the only uses of solar energy in Maine that have the potential for affecting electricity supply and demand. Widespread use of solar heating systems is possible by 1985 only if costs decrease to $10 to $20/sq. ft. collector. The federal and state governments' policies as well as the electric utility's policy toward solar space and water heating systems will have a major effect on the rate at which the systems are installed.

2. If solar heating and hot water systems were installed in large numbers (50% of residences by 1985) up to 65MW of equivalent central station capacity might be provided, with an associated reduction in fossil and nuclear fuel use. While this indicates desirability of encouraging solar, such estimates are too small and unreliable to justify the delay of the Sears Island plant.

3. At current fuel prices, central station solar thermal electric plants are not competitive with available technologies. Such plants will first become competitive in the Southwest USA.

4. Solar photovoltaic cells are not cost-competitive now, but if 1985 DOE target goals are met, photovoltaic cells could become economically feasible for decentralized systems in Maine. Manufacturing capacity would limit their use until the late 1980's or early 1990's.

5. Concepts of orbital stations with microwave transmission of electrical energy back to ground level are certainly out of the question as a competitor with conventional power stations before the year 2000.

6. Both solar cell and electrical storage technology will have to progress considerably and costs decrease markedly in order that terrestrial photovoltaic electric base power generation be competitive with conventional means.

7. Numerous institutional and technical barriers remain before dispersed solar units can effectively be integrated into the existing power grid.

8. Table 4.1 contains the best available data on the cost of electricity generated at central station plants.

7.0 REFERENCES AND BIBLIOGRAPHY

Aerospace Corp., "Solar Thermal Conversion Mission Analysis, Southwestern United States Insolation Climatology," Aerospace Corp. Report ATR-74 (7517-16)-2, Vol, III, 1974.

Albert, P. G. and S. W. Holt, "Solar Assisted Heat Pump Performance Operation During January and February 1976," Dept. of Mechanical Engineering, University of Maine, September 1976.

Anderson, B., with M. Riordan, Solar Home Book, Cheshire Books, Harrisville, N. H. 1976.

Asbury, J. G. and R. O. Mueller, "Solar Energy and Electric Utilities: Should They Be Interfaced?" Science, V. 195, No. 4277, February 1977.

ASHRAE, ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigeration and Air Conditioning Engineers Inc., New York, 1972.

Atwater, M., J. Ball and P. Brown, "Inter-Regional Variation of Radiation Data and Applications for Solar Simulation," Paper 76-WA/Sol-9, ASME, New York, 1976.

Bechtel Corp., "Energy Storage and Power Conditioning Aspects of Photovoltaic Solar Power Systems," V. I, First Quarterly Report, ERDA (NTIS COO/2748-75.II), October 1975.

Brian, D. and A. Braunstein, "Solar Radiation and Energy Measurements," IEEE PAS-95, No. 3, May/June 1976.

Boer, K. W. (ed.), Sharing the Sun, American Section of the International Solar Energy Society and the Solar Energy Society of Canada, 1976.

Boes, E. C., I. J. Hall, R. R. Prairie, R. P. Stromber, and H. E. Anderson, "Distribution of Direct and Total Solar Radiation Availabilities for the USA," Sharing the Sun, American Section of the International Solar Energy Society and the Solar Energy Society of Canada, 1976.

Caputo, R. S. and V. C. Truscello, "Solar Thermal Electric Power Plants: Their Performance Characteristics and Total Social Costs," Eleventh Intersociety Energy Conversion Engineering Conference Proceedings, Vol. II, American Institute of Chemical Engineers, New York, New York, 1976.

Caputo, R. S. "Central Station Electrical Generation," Twelfth Intersociety Energy Conversion Engineering Conference Proceedings, American Institute of Chemical Engineers, New York, New York, 1977.

Cassel, T. A. V., H. G. Lorsch, and N. Lior, "Solar Heat Pump Comfort Heating Systems," Tenth Intersociety Energy Conversion Engineering Conference Proceedings, American Institute of Chemical Engineers, New York, New York, 1976.

Chalmers, B., "The Photovoltaic Generation of Electricity," Scientific American, V. 235, No. 4, October 1976.

Converse, A. O., "The Assessment of Solar Heated Buildings and Panels," Research Program on Technology and Public Policy, Thayer School of Engineering, Dartmouth College, Hanover, N. H., Quarterly Progress Reports, 1975-76.

Cooper, V. R., and J. W. Pepper, "Rationale for the EPRI Thermal-Mechanical Energy Storage Program," presented at American Power Conference, Chicago, April 1976.

Council of Environmental Quality, "Energy Alternatives: A Comparative Analysis," (NTIS PB-246), U. S. Government Printing Office, Washington, D.C., August 1975.

Daniels, F., Direct Use of the Sun's Energy, Yale University Press, New Haven, Connecticut, 1964 (reissued in Ballantine paperback 1974).

Dietz, Albert G. H., "Weather and Heat Storage Factors," as reported in "Space Heating with Solar Energy," in Proceedings of a Course-Symposium held at the Massachusetts Institute of Technology, August 1950. Edited by R. W. Hamilton, MIT, 1954.

Doan, J. W. et al., "The Cost of Energy from Utility-owned Solar Electric Systems, A Required Methodology for ERDA/EPRI Evaluations," JPL 5040-29, ERDA/JPL-1012-7613, Jet Propulsion Laboratory, Pasadena, CA, June 1976 (JPL Interoffice Memo 341-NSTE-1977-109, April 21, 1977, R. Caputo).

Duffie, J. A. and W. A. Beckman, Solar Energy Thermal Processes, John Wiley, New York, 1974.

Duffie, J. A. and W. A. Beckman, "Solar Heating and Cooling," Science, V. 191, No. 4233, January 16, 1976a.

Duffie, J. A., W. A. Beckman, and J. G. Dekker, "Solar Heating in the United States," ASME-76-WA/Sol-8, December 1976b.

Easton, C. R., R. W. Hallet, Jr., S. Gronich, R. L. Gervais, "Evaluation of Central Solar Tower Power Plant," (McDonnell Douglas Astronautics Company), pp. 271-276 of 9th Intersociety Energy Conversion Engineering Conference Proceedings, San Francisco, CA, August 26-30, 1974. New York: American Society of Mechanical Engineers (1974).

ERDA, Solar Energy: A Bibliography, (NTIS TID-3351), Washington, D.C., 1974.

ERDA, "Terrestrial Photovoltaic Power Systems with Sunlight Concentration," Annual Progress Report for Period January 1, 1975 to December 31, 1975, ERDA Report No. CDO-2590-1(2), 1976.

ERDA, "Central Receiver Solar Thermal Power System -- Phase I, 10-MW Electric Pilot Plant," ERDA Publication SE-103, U.S. Government Printing Office, Washington, D.C., 0-220-067, 1976.

ERDA, "Photovoltaic Conversion Program Summary Report," ERDA 76-161, November 1976.

Federal Energy Administration, Buying Solar, U. S. Government Printing Office (0410018-00120-4), Washington, D.C., 1976.

Feldman, S. I., B. Anderson, et al., "Utility Pricing and Solar Energy Design," NSF/RANN #APR-75-18006, Clark University, September 1976.

Florschuetz, L. W., "Extension of the Hottel-Whiflier-Bliss Model to the Analysis of Combined Photovoltaic/Thermal Flat Plate Collectors," Sharing the Sun, V. 6, 1976.

French, E. P., "Deterministic Insolation Estimates for Solar Total Energy Systems," Proceedings of the Twelfth Intersociety Energy Conversion Engineering Conference, IEEE Catalogue No. 77CH12633, New York, New York, August 1977.

General Electric, "Conceptual Design and Systems Analysis of Photovoltaic Systems," Report No. ALO-3686-14, March 1977.

Gervais, R. L., "A Central Receiver Solar System Applicable to Central Power Stations," paper in Sharing the Sun, Vol. 5, American Section of the International Solar Energy Society and the Solar Energy Society of Canada, 1976.

Glaser, P. E., "Solar Power from Satellites," Physics Today, February 1977.

Goodenough, J. B., "The Options for Using the Sun," Technology Review, October/November 1976.

Grimmer, D. P. and K. C. Herr, "Solar Process Heat from Concentrating Flat-Plate Collectors," Sharing the Sun, Vol. 2, American Section of the International Solar Energy Society and the Solar Energy Society of Canada, 1976.

Hazelrigg, G. A., "Space Power System Design and Development from an Economic Point of View," ECON, Inc., Princeton, N. J., Proceedings of the Twelfth Intersociety Energy Conversion Engineering Conference, Washington, D.C., August 1977.

Hoover, D. O. and A. D. Watt, "Potential Role of Solar Thermal Electric Power in the U. S.," IEEE Paper A-75 516-5, May 1975.

Jordan, R. C. (ed.), Low Temperature Engineering Application of Solar Energy, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., New York, 1967.

Justos, C. G., "Wind Energy Statistics for Large Arrays of Wind Turbines (New England and Central U. S. Regions)," Final Report, Georgia Institute of Technology, School of Aerospace Engineering, August 1976.

Koomanoff, F. A., "Monitoring the Solar Resource," Paper in Sharing the Sun, Vol. 1, American Section of the International Solar Energy Society and the Solar Energy Society of Canada, 1976.

Kreider, J. and F. Kreith, Solar Heating and Cooling, Hemisphere Publishing Co., Washington, D.C., 1975.

Leonard, S. L., "Final Report: Mission Analysis of Photovoltaic Solar Energy Systems," Aerospace Corporation, El Segundo, CA (NTIS ATR-75 7476-01-1), December 1975.

Lilien, G. L. and P. E. Johnston, "A Study of the Potential for and Impact of a Solar Water Heating Industry in New England," Dialogue, Inc., Newton, Mass., July 1976.

MITRE, "An Economic Analysis of Solar Water and Space Heating," ERDA DSE-2322-1, November 1976.

Maine Office of Energy Resources, "Discussion Paper on the Direct Use of Solar Energy in Residential and Commercial Buildings in the State of Maine," March 1977.

Massachusetts Energy Policy Office, "The Use of Solar Energy for Space Heating and Hot Water," April 1976.

Massdesign, Solar Heated Houses for New England and Other North Temperate Climates, Cambridge, MA, 1975.

Massui, R. and T. Fujita, "Economics of Internal and External Energy Storage in Solar Power Plant Operation," Paper No. 779188 of the Proceedings of the Intersociety Conference on Energy Conversion Engineering, Washington, D.C., August 8 - September 2, 1977, published by the American Nuclear Society, La Grange Park, Ill., 60525.

Meinel, A. and M. Meinel, Applied Solar Energy, Addison-Wesley, Reading, 1976.

Moore, R. E., "Cost Predictions for Photovoltaic Energy Sources," Solar Energy, Vol. 18, No. 2, pp. 225-234.

National Academy of Sciences, Energy for Rural Development (NTIS PB-260) Washington, D.C., 1976.

Newkink, H. Flat Plate Solar Collector Handbook - A Survey of Principles Technical Data and Evaluation Results, Lawrence Livermore Laboratory, Livermore, 1976 (NTIS UCLD 17086).

Page, A., et al., "Maine Comprehensive Energy Plan - Vols. I, II, III - 1976 Edition," Maine Office of Energy Resources, Augusta, Maine, 1976.

Ranakumer, R., H. J. Allison and W. L. Hughes, "Solar Energy Conversion and Storage Systems for the Future," IEEE Trans. on PAS Vol. PAS-94, No. 6, November/December 1975, pp. 1926-1934.

Robbins, R. L., "Law and Solar Energy Systems: Legal Impediments and Inducements to Solar Energy Systems," Solar Energy, Vol. 18, No. 5, 1976.

Schoen, R., A. S. Hirshberg, J. M. Weingart, and S. Stein, New Energy Technologies for Buildings, a report to the Energy Policy Project of the Ford Foundation, Ballinger Publishing Co., Cambridge, MA, 1975.

Schuze, W. D., S. S. Ben-David, J. D. Balcomb, et al., "The Economics of Solar Home Heating," prepared for the Joint Economic Committee of the U. S. Congress, January 1976.

Solar Energy, The Journal of Solar Energy Science and Technology, published by the International Solar Energy Society (U. S. address: International Solar Energy Society, c/o Smithsonian Radiation Biology Lab., 12441 Parklawn Dr., Rockville, MD 20852).

Stone and Webster Engineering Corporation, "Southwest Project Resource/Institutional Requirements Analysis, Phase I Report," prepared for Federal Energy Administration, December 1976.

Thirring, H. Energy for Man, Indiana University Press, 1958, reprinted by Harber Colophon Books, 1976.

Thomas, A. and M. P. Thekackara, "Experimental and Theoretical Studies on Solar Energy for Energy Conversion," Sharing the Sun, Vol. 1, American Section of the International Solar Energy Society and the Energy Society of Canada, 1976.

U. S. Department of Commerce, Climatic Atlas of the United States, Government Printing Office, Washington, D.C., 1968.

Vant-Hull, L. L., "Methods for Estimating Total Solar Flux in the Direct Solar Beam at Any Time," paper in Sharing the Sun, Vol. 1, American Section of the International Solar Energy Society and the Energy Society of Canada, 1976b.

Yellott, J., "Solar Energy Utilization for Heating and Cooling," Government Printing Office 038-000-00188-4, Washington, D.C., 1976. (Chapter 59 of ASHRAE Handbook).

Zarem, A. and D. Erway, "Introduction to the Utilization of Solar Energy," McGraw-Hill Book Co., New York, 1963, pp. 211-238.