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SOLAR ENERGY

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SOLAR ENERGY

THE USES OF SOLAR ENERGY

It is widely recognized that the inexhaustable energy of the sun is received on the earth in sufficient quantities to make major contributions to the future energy needs of the world. However it is yet uncertain and controversial whether we now have the means to economically collect and convert that solar energy into forms useful for our needs. In this article we will review the approaches to solar energy conversion, and assess the status and economic feasibility of the technologies involved. It is helpful in defining these various approaches to solar energy conversion to distinguish between technological and natural collection of solar energy.

Technological Collection

The approaches defined here have the common feature that the initial collection and conversion of sunlight occurs within a man-made device.

HEATING AND COOLING OF BUILDINGS The heating and cooling of buildings, and some other applications such as the drying of crops or heating water for industrial processes, can be achieved by collection of solar energy in "flat plate" collectors. Such collectors do not concentrate sunlight; they consist merely of a black surface directed skyward and covered by one or more transparent covers to prevent loss of heat. Such collectors easily achieve temperatures of 100°C. Heat is obtained from the collector by circulating water or air through it, and the heat is then stored for later use.

SOLAR THERMAL CONVERSION In solar thermal conversion, solar energy is collected as high temperature heat, generally by means of mirrors or lenses that track the motion of the sun and direct a concentrated solar flux onto a receiver. Temperatures up to 500°C can be generated by this means, high enough to produce the high pressure steam used in modern steam turbines to generate electricity.

PHOTOVOLTAIC CONVERSION Photovoltaic conversion is a nonthermal process for the production of electricity directly from solar energy. Incident sunlight is used to create free charges in a semiconducting material, and the charges are then collected at the surface of the material by metallic contacts. The familiar example of this is the use of solar cell arrays to power satellites.

Natural Collection

Natural collection of solar energy occurs on the surface of the land and oceans of the Earth, giving rise to wind and weather, the growth of plants, and warm surface waters in the oceans. Each of these energy forms can then be further converted by man for his purposes.

WIND ENERGY It has been estimated that the power contained in the winds over the continential U.S. and the arc of Aleutian islands extending from Alaska is about 10^{11} kW (1), greatly exceeding the present electrical generating capacity of the U.S. of about 4×10^{8} kW. The winds at many potential sites are very strong and remarkably repeatable and predictable. Large wind turbines, erected on large plains or along the continential coast, can efficiently extract the momentum in this moving air and generate electricity.

BIOCONVERSION The energy stored in organic matter (often referred to as biomass) by the photosynthetic process can be used for the production of clean fuels. In a bioconversion process, the methods now being developed for utilization of the energy in urban waste would be applied to convert to fuels crops grown specifically for their energy content. The products of conversion processes can be either synthetic natural gas, or liquid fuels, such as alcohol, that can replace gasoline. If through advanced agricultural practices, including the modification of plant genetics, energy plantations were operated to produce crops continuously through the year at a 3% conversion efficiency, then only about 2% of the U.S. land area could provide stored solar energy equivalent to the present U.S. electrical requirements.

OCEAN THERMAL CONVERSION Between the Tropics of Cancer and Capricorn where the average intensity of solar energy is at a maximum, 90% of the Earth's surface is water. The incident solar energy heats this surface water to temperatures up to 85°F, while the waters at depths below 600 meters remain cold, typically 35 to 38°F. A heat engine can operate across this temperature difference, though only at about 2% efficiency. The amount of heat in these surface waters is so large that even at this efficiency immense amounts of energy are available. Conversion of only the heat contained within the Gulf Stream would provide 700×10^{12} kWe (1).

These various approaches to solar energy conversion can be seen to span a wide range of technologies. Some are very well defined and are now entering the stage of commercial application, while others require significant research to establish their technical feasibility. However, they are all potential uses of solar energy, and it is the purpose of this review to introduce the reader to the many technical, economic, and other issues that surround their future development and utilization.

THE SOLAR RESOURCE

The use of solar energy adds a new consideration to the design of any system, that is, the energy source is variable. As the sun crosses the sky, its intensity at a point on the earth's surface varies due to the geometric effects associated with its position and the changing effects of attenuation and scattering by the intervening atmosphere.

The intensity of solar radiation on a surface normal to the sun's rays above the atmosphere, known as the solar constant, is 1353 W/m^2 (2). This radiation has a relatively smooth spectral distribution of wavelengths from 0.3 to 3 microns. The solar intensity on a surface normal to the sun's rays, but located at the earth's surface, is attenuated by water vapor and dust in the atmosphere, and is also scattered, thereby forming the diffuse portion of the solar energy reaching the surface. The intensity of solar energy at noon on a clear day is about 1000 W/m^2, with most of this energy in the form of direct radiation. The clear sky solar intensity (direct and diffuse) has been monitored at several locations in the U.S. and the data generalized for engineering design (3,4).

While clear day insolation values are helpful in designing a solar system, account must be taken of cloud cover. This may be accomplished by using insolation data from a previous year, or the average of several previous years, for the site being considered. The National Weather Service network has monitored the number of sunshine hours per day, total solar radiation and, in some cases, the direct (normal incidence) component of solar radiation at 90 sites throughout the U.S. (5). The basic insolation instruments are the pyranometer (for total radiation) and the pyrheliometer (for the direct component).

Ideally, the performance of thermal collection systems should be independent of spectral distribution of the insolation and depend only on the total intensity. However, the performance of selective absorbers and of cover materials is optimized only over a particular spectral region and their degradation has a definite spectral dependence. The output of photovoltaic devices is strongly spectral-dependent, as is the natural photosynthetic process and other photochemical processes.

It is important in comparing different techniques for collecting solar energy to note that non-concentrating collectors (such as flat-plate collectors and photovoltaic cells) can utilize diffuse as well as direct radiation. Since solar thermal systems employ a concentrating collector of some kind, only the direct component of the radiation is useful. This difference can be critical in locations where the sky is often overcast.

Solar energy arrives at the surface of the U.S. at an average rate of 4.76 $KWhr/m^2$-day (1), so over a year a square kilometer would receive 4.4×10^9 KWhr. In 1974, the total energy consumed by the U.S. for all purposes was about 2.4×10^{13} KWhr. Accordingly, 55,000 square kilometers of land, dedicated to solar energy conversion at 10% efficiency, could meet, on the average, the entire 1974 U.S. energy requirement.

The situation changes somewhat when one compares the energy densities of various users to that of the solar radiation. The energy arriving on the roof of a typical home over a year is several times greater than the thermal energy needs of that building. The same is true for the electrical needs of a single home. However, as the energy density of the application increases, as, for example, one moves from single family dwellings to large apartment buildings, it becomes impossible to obtain sufficient energy from the solar energy received only on the land occupied by the building. Land dedicated to the conversion of solar energy will be necessary for such high-density applications.

STATUS OF SOLAR ENERGY TECHNOLOGIES

Heating and Cooling

Of the promising applications of solar energy, heating and cooling of buildings with solar energy is generally considered to be the closest to commercial availability. The history of solar energy utilization for heating and cooling of buildings began in the U.S. with the use of solar water heaters in Arizona, California, and Florida in the early 1900's (4). Just as with wind generators, their use declined with the availability of low cost energy from fossil fuels. Interest in space heating with solar energy developed in the 1930's first with the utilization of large south-facing windows to admit winter sunshine, and then with the application of separate collectors used in conjunction with some form of thermal energy storage. Insulated tanks of water, rock beds, and materials that undergo a change of phase with absorption of heat, were all used (6).

Beginning in the 1940's, and continuing into the early 1970's, a series of experimental houses were built to test many different solar heating concepts. These include, among others, the MIT houses, Löf's houses in Colorado, the Telkes house in Massachusetts, an office in Princeton, N.J., the Bliss home, the Hay building, the University of Arizona solar laboratory in Arizona, the Bridgers and Paxton office building in New Mexico, the Thomason homes in Washington, D.C., and the University of Florida and the University of Delaware houses (4,7). Essentially all of these buildings were financed by individuals, foundations or universities, with the goal of demonstrating that solar energy could provide most of the heat needed by the building and that air conditioners driven by solar heat (or nocturanal radiation) could provide the cooling.

The high cost of the equipment used in these pioneering experiments prevented solar heating from moving into the market place. While the recent major research, development, and demonstration efforts have brought many of the technical aspects of such applications under investigation, the status of their utilization has not yet changed significantly. Solar water heaters, commercially available in Australia, Japan, India, Israel, and the USSR, are not appreciably used in the U.S. Solar heating systems have been successfully demonstrated in ever growing numbers and are becoming commercially available, but for widespread use to occur, prices must be lowered further (8).

The thermal and operational performance of the major components for solar heating and cooling systems must be improved. Existing components have generally not had the adequate development and testing that would insure long-lived performance at design conditions (8). The most common collector for solar heating and cooling today is the flat plate collector. This collector typically consists of a metal absorber plate (painted black or coated with a high absorptivity, low emissivity material called a selective surface) to which fluid passages are attached. One or two glass or plastic covers on top and insulation on the bottom serve to reduce thermal losses (9). Work is underway to further reduce the thermal and optical losses by means of evacuated spaces, honeycombs, special materials, concentration, and tracking, thereby making it practical to operate the collector at higher temperatures (10).

A variety of methods for solar cooling are under investigation, including absorption refrigeration, adsorption, heat pumps, rankine/vapor compression, and nocturnal radiation. More effort is needed to identify the most promising approaches, and to determine how solar cooling is to be integrated into a heating and cooling system (11).

In the solar heating and cooling systems tested to date, the thermal energy storage medium has usually been water. Since it seems likely that water, with its numerous advantages, will continue to be widely used for thermal energy storage, better containers must be developed. The present experience with phase change materials suggests that significant research and development is still needed before acceptable storage units using this method are available (12). Related to these major components, and in need of considerable improvements, are the heat transfer fluids, the various heat exchangers and the control systems.

There have been several plans proposed to establish the widespread availability and use of solar energy for meeting the thermal needs of all types of buildings throughout the U.S. The present Energy Research and Development Administration plan (8), formulated in accordance with the 1974 Solar Heating and Cooling Demonstration Act, places major emphasis on a series of demonstrations. Earlier plans such as that suggested by the NSF/NASA Solar Energy Panel (1) and by the National Science Foundation, as reported in the Project Independence Report (13), while emphasizing a strong demonstration effort, place more emphasis on the development of improved components and subsystems. The ERDA plan consists of three parallel efforts. The major effort is the demonstration of residential and commercial solar heating and cooling systems. A second effort is the development of improved components for use in the demonstration systems, and a third effort is the research and development on advanced technology for heating and cooling systems.

The relative nearness of this particular solar energy application has evoked considerable public attention, interest and controversy. In numerous hearings, arguments have arisen concerning the roles of small business vs. large industry, the importance of research vs. demonstration, the role of tax incentives and subsidies, and how many demonstration projects are needed to succeed in stimulating the creation of a viable industrial and commercial capability for producing and distributing solar heating and cooling systems. The motivation is indeed great, for the use of such systems in just 1% of the buildings of the U.S. could save approximately 30 million barrels of oil per year (14).

Solar Thermal Conversion

The technology of solar thermal conversion dates back to an exhibition in Paris in 1878 where sunlight was focused onto a steam boiler that operated a small steam engine. A more complex system was built by Harrington in New Mexico half a century ago. He focused sunlight onto a boiler and ran a steam engine which pumped water uphill into a storage reservoir. Water drawn from the reservoir operated a turbine and generated the electricity that lighted a mine (15). Harrington's system had all the functions usually proposed for contemporary solar thermal conversion facilities: light collection and concentration, conversion to heat, storage of energy, and generation of electricity. These systems and others, built and operated during the last 100 years (16), demonstrate that an adequate technological base for solar thermal conversion does now and has long existed.

What remains to be resolved are the answers to three fundamental questions about solar thermal conversion. Can solar thermal conversion become economically competitive with combustion of fossil fuels as a source of high temperature heat? What are the best designs for the collection and conversion of sunlight in a solar thermal facility? What are the best uses of the high temperature heat from solar thermal conversion? The first of these questions we will address below, under the topic, The Economics of Solar Energy. In the present section we will review the status of work on the latter two questions, regarding the technology of solar thermal conversion.

COLLECTION AND CONVERSION Two basic techniques, employed singly or in combination, are used to achieve production of high temperatures from solar energy. The temperature to which a surface is heated by a certain flux of incident solar energy is determined by the balance of incident radiation and loss by conduction, convection and radiation. Given that measures are employed to restrict loss by conduction and convection, then achievement of high temperature at a certain solar flux results from use of a selective surface that absorbs visible sunlight but does not lose energy by radiation of infared (9).

The temperature obtained from solar energy can be increased by boosting the flux of incident sunlight by using concentrating mirrors or lenses. This method is carried to its extreme in the solar furnaces that have been built and operated to conduct materials research at temperatures as high as 4,000°K (17,18,19). These furnaces employ a much higher concentration ratio than necessary for generation of electricity or most process heat applications, so they are not actually prototypes of solar thermal conversion facilities. However, they can be usefully employed as test beds for solar thermal components.

The techniques of selective surfaces and concentration can be employed in combination. Thus a fairly low concentration ratio, obtainable with simple optics, can be combined with a selective surface to efficiently produce temperatures high enough for electrical power generation.

We can distinguish three basic geometries for collection of sunlight for solar thermal conversion: non-concentrating, concentrating to a line, and concentrating to a point. It is difficult to operate practical cycles for conversion to electricity at the temperatures available without any concentration (20). However, nonconcentrating collectors with selective surfaces may be useful for providing industrial process heat at moderate temperatures. With concentration to a line, concentration ratios of about 10 to 20 can be achieved. Of particular interest is the Winston collector which achieves moderate concentration to a line without need for tracking the sun (21). Line focusing, alone or in combination with selective surfaces, provides temperatures high enough for electrical generation (22). With point focusing, concentration ratios can be as high as 1000, though lower ratios are sufficient for electrical generation (23). There is probably no need for use of selective surfaces in a point focusing system.

Of these various configurations for collection and conversion to heat, the central tower/heliostat design (24) is now favored for the first solar thermal pilot plant (25). In this design, a field of heliostats (trackable mirrors), perhaps 15,000 individually controlled units of about 36 m^2 area each, would reflect sunlight to the top of a tower at the center of the field. Each such tower would collect heat sufficient to generate about 50 MW of electricity (25). The concentration ratio in this design is quite high, and selective surfaces are not required. The high temperature heat is collected at the top of the tower in a working fluid, perhaps water/steam or an eutectic salt (26), and piped to the ground for use in electrical generation or another high temperature application.

APPLICATIONS Most of the present effort in solar thermal conversion is directed toward the generation of electric power in large central plants for distribution in an electric power network. Within this application there are various options. The solar thermal plant could be run as a base load, in which case it would require a large amount of energy storage and provide power to the network almost constantly day and night. Or it could be run as an intermediate load plant, providing power for about 12 hours a day, with a smaller storage requirement. Finally, it could provide only peaking power, and require very little energy storage capacity. The comparative study of these possibilities by the Aerospace Corporation has identified the intermediate load plant as having the best economics (25).

There are significant opportunities for the use of solar thermal conversion in providing industrial process heat. About 18% of the fuel consumption in the U.S. is for generation of industrial process heat at moderate temperatures (process steam) and another 11.5% is used for high temperature process heat (27). Solar thermal conversion facilities to provide process heat could be sited at the plant requiring the heat, and could be sized to match the requirements of the plant. A demonstration of the use of low temperature solar heat in an industrial process is now being built at the Sohio uranium mining and milling complex in Grants, N.M.(28).

Photovoltaic Conversion

The photovoltaic effect, noted by Becquerel in 1839, is the basic process of solar cells, which were first fabricated in 1954 by workers at RCA and the Bell Laboratories. Photovoltaic conversion systems are based on the absorption of light in semiconducting materials to generate free charges that drift across a junction between two types of semiconductors and are collected at contacts applied to the exterior surfaces of the material. The theoretical limit to efficiency for conversion of solar energy to electrical energy is about 25% for a single semiconductor device operating at room temperature. While the early silicon cells achieved an efficiency of only 5%, present solar cells operate at 10-15% with efficiencies approaching 25% predicted for the near future (29). The "single crystal" silicon solar cell has been the mainstay of photovoltaics. Solar cells have also been developed from other materials, including most notably cadmium sulfide and gallium arsenide.

The silicon cell has been integrated into arrays and the output conditioned to meet the electrical energy demands of satellites. The 50 kW Spacelab power system is the largest such solar cell system built to date. Terrestrial applications have been limited to small units for remote applications such as recharging batteries on offshore drilling platforms, microwave repreater stations, and bouys and other navigational aids. Two larger experimental systems that provide on-site electric power to meet residential needs are now in operation: a combined photovoltaic and thermal system using cadmium sulfide cells (30) and a 1 kW silicon array whose electrical energy output is used to produce hydrogen by electrolysis (31). The present cost for these solar cells is about $50/peak watt.

Silicon is the Earth's second most abundant material, and the cost of the metallurgical grade material from which the cells are made is only $600/ton. However, because of the way silicon cells are produced, they are very expensive. The basic production process used in the past incorporates some 50-60 steps with numerous heating and reheating operations, and begins with the growing of a single crystal out of molten silicon by the Czochralski process. This batch process is slow and expensive, and does not lend itself to mass production. A subsequent sequence of cutting and polishing steps, with considerable loss of silicon material, preceeds the formation of the semiconductor junction and attachment of the electrical contacts (32).

Obviously, improvements can and are being made, with process steps being consolidated or eliminated. Even without additional technical improvements, significant cost reductions can be realized by the application of mass production techniques. It has been predicted that if the present annual market of cells with a total peak capacity of 60 kW were increased to about 100 kW a decrease in the silicon array price to $5/peak watt would occur (33). However, this price is still too high and new approaches are being developed that hold the promise of further cost reductions. A goal of less than $0.50/peak watt has been set for achieving economic competitiveness of large-scale terrestrial photovoltaic systems with future fuel prices.

In order to achieve this additional factor of 10 or more cost reduction, it will be necessary to lower the cost of the starting material. Recent studies have shown that solar cells with good electrical characteristics can be made of a lower grade, and accordingly less expensive, silicon. This development, coupled with a new production technique called the Edge-defined, Film-fed Growth (EFG) process, supports an expectation that solar cells costing less than $0.5/peak watt can be produced. The basic idea of the EFG process is to insert a die into the crucible containing the molten silicon. The liquid rises through the die and crystallizes as it is removed from the top. Ribbons of silicon meters long and about 5 cm wide have been made with this process. Since additional silicon can be added to the melt while the process is in operation, it is a continous process which lends itself to the production line.

Many other semiconductors besides silicon exhibit a photovoltaic effect. Of these, cadmium sulfide-copper sulfide has received the most attention. Although many of these devices have the potential for high-volume production and for costs less than that of single crystal silicon cell arrays, they appear to require far more research and development (34). A wide variety of these devices are presently being studied.

The challenge in the development of photovoltaic technology is to produce arrays which can be used to generate electricity on an economically competitive basis. Within the next ten years the practicability of a photovoltaic system having array costs less than 50 cents per peak watt should be established. The electricity cost for a residence requiring an average power of 1 kW would then be 40 to 50 mills/kW hr (13). The major effort will most likely be made with the single crystal silicon cell. A low cost, high volume process for producing the raw silicon starting material must be developed, along with a method for producing large silicon crystals. Finally, an automated cell and array fabrication and encapsulation method must be devised to complete the process. In order to keep the area of the arrays reasonable, the efficiency of the cell must be maintained at its present level of about 16% or higher; 20% being a reasonable goal.

A series of system experiments and demonstration projects is being planned. These systems, increasing in size from several kw to several hundred kw, will provide a market stimulus for the cell manufacturers and will provide system performance data. An analysis is underway of the criteria to be used for selection of preferred applications within the categories of on-site generation, central station generation, and fuel production (35). The question of system scale, small to very large, and system function, baseload, intermediate, or peaking power, must also be addressed.

Production of Fuels

Among technologies for large-scale production of useful fuels from solar energy, those that utilize the natural photosynthetic process in plants or algae are best established and thus potentially important for the near future. These include energy plantations on land, ponds for growth of algae or water plants, and ocean-sited kelp farms. Alternatives to the natural photosynthetic process, such as photochemical conversion or solar-thermochemical conversion, are under investigation but are still at the stage of basic and applied research. These alternative techniques are potentially of great importance in the more distant future.

ENERGY PLANTATIONS Existing methods of land agriculture could be used now in energy plantations for the production of significant amounts of biomass to be burned directly as a low-sulfur fuel or converted to liquid or gaseous form (36). However, new crops and growth and harvesting techniques may be needed to avoid competition with food production for use of land and water. This is a severe constraint on the production of biomass for energy, because of the world-wide demand for good land and water for food crops (37). Since in an energy plantation the goal is to produce the maximum amount of biomass, crops such as euculyptus trees, rubber plants or sunflowers may be used because of their rapid growth and high productivity as measured in energy content (38,39). The energy efficiency of land agriculture is quite low, typically less than 0.5% of the solar energy being stored as biomass. However, the photosynthetic process is capable of higher efficiencies, up to 12% efficiency being noted in some experiments (40). The efficiency of energy plantations could be greatly improved if crops can be developed that perform photosynthesis efficiently in full sunlight and not lose excessive amounts of energy by respiration. Recent advances in plant cell culture and genetic modification may provide the techniques needed to develop such high energy efficiency crops (41).

ALGAE PONDS Liquid wastes from homes, industry, and agriculture contain nutrients that can support the growth of algae in ponds. Systems have been designed that use heterotrophic bacteria to oxidise waste materials to nutrients, and algae to use the nutrients and collect solar energy to produce biomass (42). Algae cultures of nearly 10^9 liters have been established, and the potential efficiency of solar energy conversion of the cultures is better than 5%. However algae produced in such ponds may turn out to have a higher value as a feed for animals than as an energy source.

OCEAN FARMS The substantial requirements of energy plantations for land can be avoided by establishing ocean farms of seaweed species with high growth rates, such as kelp. An investigation is now underway of the feasibility of constructing large subsurface structures in the open ocean that could support the growth of kelp. The immense areas of the ocean, now practically devoid of life, could then be used for kelp farms to produce food or energy. Initial results indicate such farms may be feasible, but the addition of fertilizers, especially nitrogen, to the ocean water will be required for good growth (43).

PHOTOCHEMICAL CONVERSION An attractive long-term alternative to the growth of biomass and subsequent conversion to gaseous or liquid fuel is the direct production of a fuel by a photochemical process. The process being most widely investigated is photolysis, the splitting of water to produce hydrogen. The approaches to photochemical conversion can be divided into three categories by the nature of the chemical system utilized: biological, biochemical, or synthetic.

In a biological approach whole organisms are used to conduct the splitting of water into hydrogen and oxygen; thus the term biophotolysis (44). However, the liberation of molecular oxygen generally inhibits the activity of hydrogenases, the biological enzymes that produce molecular hydrogen (45). Thus an important task for research in this area is to find species or mutations possessing hydrogenases that are effective in the presence of oxygen. An alternative is to produce the hydrogen and oxygen separately, as has been done with cultures of a blue-green algae (46). However, in all known cases of biophotolysis the rate of hydrogen production is extremely small, and great progress will be required before practical conversion schemes can be designed.

In a biochemical approach enzyme systems would be obtained from biological organisms and then combined in an appropriate reaction cell to perform all the steps involved in collecting energy and driving the water splitting reactions (45). Production of hydrogen, at least at low rates for short periods of time, has been demonstrated (47,48), but more basic research on the biochemical mechanisms of photosynthesis, and inventive ideas for incorporating molecular components into systems, will be required for this technique to become practical.

In a synthetic approach a complete chemical system for photolysis would be designed and synthesized without using any components taken from plants or algae. This has a great advantage in that problems of instability of biological components can be avoided. There are some promising ideas about the form such chemical systems might take (49,50), but this must be considered a long term research problem. An alternative to a purely photochemical approach is a hybrid of photovoltaic conversion and electrolysis, in which light falls on a semiconductor electrode in a solution and drives a water splitting reaction. This effect has been observed (51), but is far from being a practical conversion device.

THERMOCHEMICAL CONVERSION If a practical and economical technology for the collection of solar energy as high temperature heat can be developed, then a new route for the production of fuels from solar energy is opened: thermochemical splitting of water to produce hydrogen. Processes for thermochemical hydrogen production are being actively investigated because of their potential utilization with high temperature nuclear reactors (52). Hundreds of possible processes that use various reactants in closed cycles have been investigated with the aid of computer programs. Many of these were reviewed at the 1974 Miami conference on the hydrogen economy concept (53). Either point-focus solar collectors or line-focus collectors with selective surfaces could provide temperatures high enough (above 1000°K) to drive these cycles. However, these thermochemical processes are complex and might be impractical. They require at least two steps for the separate liberation of hydrogen and oxygen, and thermodynamic arguments suggest the need for more than two steps (54). Large amounts of reactants, high temperatures and perhaps high pressures, and extensive mixing, reaction, and separation steps are required (55), so the design of a practical process will be a challenging task.

ELECTROLYSIS An alternative to thermochemical production of hydrogen is to first use the solar heat to generate electricity by a solar thermal conversion scheme, and then use the electricity to produce hydrogen by electrolysis of water. Electrolysis could also be used to produce hydrogen in conjunction with any solar energy technology that leads to electricity: photovoltaic, ocean thermal or wind energy conversion. Electrolysis is a proven technology that has been used commercially in both small and large applications (53). Efficiencies are good, with only about 115 kW-hr of electricity required to produce 1,000 cu. ft. of hydrogen, for an energy efficiency of 83% (56).

Wind Energy Conversion

Prior to and during the early 1900's, wind energy was widely used in rural areas of the U.S. to provide motive power for grinding crops, pumping water for irrigation, and charging electric batteries. The widespread availability of inexpensive electricity in the 1930's, brought about largely by the efforts of the Rural Electrification Administration, caused a decline in these small scale uses of wind energy from which they have not recovered. A number of large experimental wind machines, designed for electric power production with capacities of 100-1000 kw have been developed. The largest of these machines, the 1.25 MW Smith-Putnum wind generator, built in 1941 on Grandpa's Knob in Vermont, proved that a practical machine could be built which would generate electricity in large quantities and feed into an electric power network. A large number of turbines for electrical power generation were also built in Europe. However, in spite of many technical improvements, these machines were unable to compete with the declining price of electricity from fossil fuels (57,58).

The rising fuel prices of the 1970's, coupled with three decades of technological advances, has renewed interest in the possibility that economically attractive wind energy systems can now be designed (59). For these systems to have a significant impact on the national scale will require not only improvements in the performance of major components, but also development of new design concepts and applications. In addition, the wind energy resource must be assessed and techniques developed to predict the wind characteristics at potential sites for these systems.

The energy available to a wind turbine is the kinetic energy of the wind passing through the area swept by the blades of the turbine. This energy flow increases with the cube of the wind velocity, so selection of sites is of great importance. Theoretically, 59.4% of this energy would be extracted by a perfectly designed turbine (60). The efficiency actually achieved by a well-designed turbine is about 45%, and an overall system efficiency of 30 to 40% for generation of electricity can be obtained. Thus the blades of a turbine intended to provide 1 MW of power from a wind of 25 mph would have a diameter of about 300 ft.

At present, new concepts are being studied for improved rotors and energy storage and conversion components. The interaction of wind turbine systems with electric power networks is being investigated to assess the need for energy storage or back-up generating capacity. In addition, the possibilities of on-site wind conversion for industrial or agricultural applications are being studied.

A sequence of experimental and demonstration systems are planned for construction, ranging from small units, less than 100 kw, for rural applications, to large multi-unit systems in the 10-1000 MW range (61). The 100 kw experimental wind turbine generator presently under construction at the NASA Lewis Research Center and scheduled to commence tests in 1975 is the first large wind machine in this sequence (62).

Ocean Thermal Conversion

Though the concept of generation of electricity from naturally occuring ocean temperature differences dates from the 19th century, the only attempt to demonstrate its feasibility has been a series of experiments conducted by Claude in 1929 (63,64). In these experiments, Claude attempted to operate a heat engine between the warm surface waters of the tropical oceans and the cold waters at depth. However, Claude used the ocean water itself as the working fluid, so the high pressure supply to the turbine was limited to the vapor pressure of the warm surface water. Claude's experiments were of limited success for a number of reasons, including the large amounts of energy required for pumping, and the problems of protecting the plant from vagaries of weather. The use of water as the working fluid cannot be ruled out on the basis of his experiments, but current proposals generally favor a secondary working fluid with a higher vapor pressure than water (65).

The concept of ocean thermal conversion has been revived and further developed by a number of advocates, including the Andersons (66) and Zener (67).

A number of conceptual designs have been prepared and operating efficiencies and economics estimated (68,69,70). An important element of these designs is development of heat exchangers with low cost per surface area and small temperature drop from the ocean waters to the working fluid, which may be ammonia, a fluorocarbon refrigerant, or an organic fluid such as propane. In general, these studies have reported favorably on the technical feasibility of ocean thermal conversion, and have argued strongly for its economic feasibility.

Reviews of the ocean thermal conversion concept have recently been performed by TRW Systems and Energy Group, and by Lockheed (71). These reviews, intended to provide an independent assessment of the concepts being advanced by advocates of ocean thermal conversion, have generally concluded that the technical problems of the systems can be solved, and that the economics of the systems are promising.

THE ECONOMICS OF SOLAR ENERGY

Though it is often said solar energy is free, this is no more true for solar energy than for any other energy resource. Oil in the ground costs us nothing: nature and time have provided it. However, to extract, transport, refine, and distribute oil to the consumer costs us in both labor and capital. The same is true of solar energy: the cost is in the labor and capital required to make it useful to our needs.

Solar energy does differ from most of our present energy sources in that it is very intensive in "first cost". Thus in comparing a solar thermal power plant with a coal-burning plant, we must decide how to compare flows of costs and benefits that have different distributions in time. This question of how to compare the present and future utility of alternatives is a subtle and difficult problem in economics. The question has ramifications at the level of the individual decision by a single firm or individual consumer (e.g., choosing between a solar and a coal-burning plant for required new generating capacity), and at the level of how a nation should influence by policy the transition from energy sources of finite extent such as petroleum to inexhaustable sources such as solar energy.

Discounted Cash Flow

First we consider how a single firm or individual will make an economic comparison of a solar energy technology with an alternative technology that requires continuing purchases of fuel in the future. For a single firm, the comparison between the present and the future is essentially determined by the interest rate the firm must pay to borrow money (the cost of capital). If the interest rate is r, to invest one dollar in capital equipment now will cost the firm $(1 + r)^n$ dollars when it repays the loan n years later. Thus $(1 + r)^n$ dollars n years in the future is worth one dollar now, or equivalently, one dollar n years in the future is worth only $(1 + r)^{-n}$ dollars now (72). If one wishes to compare two investment alternatives that have different schedules of payment and return, then this can be done by discounting (multiplying) all future costs and income that will occur n years in the future by the factor $(1 + r)^{-n}$ and summing over all future years. This is the discounted cash flow method of investment analysis. It serves to translate all future costs and payments into their present value (73).

For normal interest rates, and for the periods of service generally considered for solar energy facilities, this discount factor strongly influences economic comparisons. For example, one dollar saved in fuel twenty years from now is worth only 0.148 dollars in present value if the interest rate is 10%. Thus a company that must pay 10% interest ought not pay more than 0.148 present dollars for a solar energy system to save one dollar of fuel twenty years from now. One sees that a high discount rate tends to discourage investment in facilities with high initial costs that have a stream of benefits extending into the future, such as solar energy systems. Thus policies that serve to provide low interest rates for solar energy facilities can be very effective in improving their economic competitiveness.

Future Energy Prices

A major source of uncertainty in comparing solar energy technologies to present technologies is the future price of fuels, including oil, natural gas, coal, and uranium. If fuel prices rise faster than the interest (discount) rate, then solar energy systems with quite high initial costs will be shown more economical in a discounted cash flow analysis. Some analyses of the economics of solar energy applications have assumed rates of price increases for fuels as high as 14%. Experience of the last year is certainly consistent with such high rates, however, to assume that such rates of increase will continue for 20 or 30 years is unjustified. This would mean an increase in energy prices of more than an order of magnitude, so that the cost of only the energy incorporated in manufactured goods, now about 5% of total cost (74), would become comparable to their total present cost. The consequences of this on the national economy would be so severe that no reasonable deductions can be made about costs of labor or capital for solar energy devices in such a scenario.

Some resource economists would actually argue that the price of energy will decrease in the long term. This school of thought is represented by Barnett and Morse, who see the effect of technological progress as more important in determining long term price trends than resource depletion (75). This would mean that solar energy technologies must come down to quite low initial costs to be competitive.

Given such a wide range of opinions about future fuel prices, any economic analysis of a solar energy facility intended to provide energy for 20 or more years is very uncertain. The best we can do is use a moderate estimate of future fuel prices, and always keep in mind the sensitivity of our analysis to any variation from our assumed prices. A moderate assumption about future fuel prices is perhaps represented by the Aerospace study of solar thermal conversion (73). They assume that natural gas prices will increase at about 7% and coal prices will increase at about 3.5% between now and the year 2000. It was assumed in this study that future oil prices will preclude its use for electrical generation.

Future Resource Use

The concept of discount analysis can also be applied to society as a whole to investigate policies that involve the use of solar energy to save finite resources for future generations. For example, we can inquire as to the relative utility (benefit to society) of consuming a barrel of oil now or saving it for use at some time in the future (76). In a discount analysis approach to distributing over time the consumption of a finite amount of oil so as to obtain optimum utility, we would discount the value of consuming a barrel of oil n years in the future by $(1 + r)^{-n}$. Thus, with a value of r about 10%, discount analysis would have us consume a barrel of oil now at a value of $10, even if it would be worth $1,000 to industry fifty years from now as a chemical feedstock. This concept of discounting the future utility of consumption has been rejected by some economists, such as Ramsey, who in developing a theory of saving states "we do not discount later enjoyments in comparison with earlier ones, a practice which is ethically indefensible and arises merely from the weakness of the imagination..." (77). However, the existence of high interest rates for investment in solar energy represents, in its effect, a policy of consuming finite energy resources now in preference to conserving them for the future.

An example of a public policy that tends to favor the utilization of capital intensive but fuel conserving technologies, such as solar energy, is the regulation of public utilities. According to the Averch-Johnson thesis, the fact that the rate of return on investment in capital by a public utility is established at a fixed percentage by the regulatory commission leads to an "oversubstitution" of capital for labor or fuel.

The oversubstitution is in comparison with the amount of capital that provides the best marginal return on investment with present fuel prices (78).

Heating and Cooling of Buildings

The economics of heating and cooling a building with solar energy depend strongly upon the local climate and upon the detailed characteristics of the building loads. Because the cost of solar system must be paid for every day, but the system returns value only when the load requirements match the presently available or stored solar energy, the economics of a system for a particular application must be estimated by an hour-by-hour analysis of the predicted loads and solar energy inputs. Methodologies for such analyses have been developed and applied to investigate the economics of systems in various climates (79-83).

Though exact economic evaluations require the detailed analysis discussed above, we can derive a simple rule that identifies the approximate requirements a solar energy system must meet for economic competitiveness. (This rule was suggested by M.A. Wahlig). Consider the type of system that employs circulating fluids in collectors and provides space heating for a building. In an average climate, about 1200 BTU fall on each square foot of collector each day. The collector is about 50% efficient, and there are about 200 days of the year when the heat can be used to meet a building load, so the amount of useful heat collected per year per square foot of collector is about 0.12 million BTU. Each year a payment must be made for the interest (about 10%) and amortization (over about 20 years). This annual payment will be about 0.12 times the initial cost of the total system. Thus, solar energy systems for buildings provide a million BTU at a cost approximately equal to the total initial cost of the system per square foot of collector. Of course this rule is very crude, and is intended only to indicate the range of allowable costs for solar components.

The present cost of moderate performance flat plate collectors suitable for space heating applications is about $6 per square foot. The cost of the remainder of the system components (storage tank, plumbing, and controls) and installation may about double this cost to approximately $12 per square foot of collector. Present (1975) prices for fossil fuels for home heating vary with region, but are about $1.50 per million BTU for natural gas and about $2.50 per million BTU for fuel oil. Thus, if one considers only present prices, solar heating is not competitive with gas or oil. However, even for a solar system to be installed now, comparison should be made with the prices to be paid for oil and natural gas over the next 20 years. In addition, for solar systems to be installed in the future, mass production, improved technology, and familiarity of building contractors with solar technology should reduce the initial cost. Based on consideration of these factors, the three Phase Zero studies of solar heating and cooling estimate solar heating systems will reach economic competitiveness with fossil fuels around 1985 (81,82,83).

The above estimates refer to fully active solar heating systems. In addition to these systems, there exists a wide range of passive or partially passive systems, including the use of overhangs above windows, drumwalls (84), and the Skytherm house (7). Many of these less complex systems are already economically justifiable, and while they do not provide full thermostat control of interior temperatures, they can greatly reduce requirements for fossil fuels.

Solar Thermal Conversion

In examining the economics of solar thermal conversion for generation of electricity, it is not sufficient to consider only the solar thermal plant itself. Instead one must consider the entire utility network which will combine solar and non-solar energy sources. In any network, the installed capacity must exceed the expected peak loads by some margin which provides for the occasions when some of the generating plants are out of service (either for planned maintenance or break-down). A solar thermal plant will also suffer insolation outages, and for this reason extra back-up capacity for the solar plant will be required in the network. Thus, an economic analysis of solar thermal conversion requires consideration of both the amount of fuel supplanted by the solar plant and the amount of installed capacity supplanted. Similar considerations apply to the photovoltaic and wind energy applications in electric power networks. This sort of margin analysis for solar thermal conversion has been performed by Aerospace Corporation (73).

The cost to a utility of a solar thermal plant is expected to be largely the cost of construction, and it is this parameter that has received the most attention. For valid comparison with the capital costs of fossil and nuclear plants, consistent methods of dealing with projected escalation of labor, equipment, and materials must be used (85). The cost estimates for solar thermal plants are dominated by the cost per square meter of the collectors (heliostats in a central receiver plant.) Estimates of the cost of heliostats for central receiver plants range from \$3.2 per square foot (23) to \$8.2 per square foot (22). With an assumed cost of heliostats of \$3 per square foot, Aerospace Corporation estimates a busbar cost of electricity of 4.8¢ per kilowatt-hour in 1991 dollars (2.8¢ per kilowatt-hour in 1974 dollars). This is within range of the projected costs for electricity from fossil fuels in 1991.

Photovoltaic Conversion

For applications of photovoltaic conversion in electric power networks, the methodology of margin analysis introduced under solar thermal conversion is relevant. However, for applications involving local generation at a residence or commercial building, a different analysis is required. Much of the cost of electricity to a small consumer is the fixed cost of distribution and service, rather than an incremental cost per unit of energy. Thus, the savings made possible by photovoltaic arrays that reduce but do not eliminate the need for electricity from the network are significantly limited. For the present, these detailed considerations are secondary to the crucial question of the cost per unit area of photovoltaic devices. The cost goals for economic competitiveness have been estimated to be about $4 for central station applications, and about $6 for residential applications, per square meter of solar array (86).

The present costs of solar cells for terrestrial applications (used in remote sites where other energy sources are not available) is about $2,000 per square meter, and the cost of the high-quality cells used in space applications is about another factor of ten higher (87). Thus, the goal in photovoltaic research and development must be to eventually reduce costs by a factor of about 500. This will require significant technological advances, in addition to the cost reductions made possible by mass production of millions of cells. Consideration of the cost of the high-purity silicon used in cells leads to the conclusion that advances in the technology for purification of silicon are also required (88).

Production of Fuels

Of the various technologies by which fuels can be produced from solar energy, only those that utilize the natural photosynthetic process in plants are well enough defined to allow economic analysis. The economics of land-based energy plantations have been examined by Inter-Technology Corporation (36) and by Stanford Research Institute (38). The assumptions used in these analyses are favorable to low production costs: locale in the southwestern US where insolation is high, adequate water supply, optimum use of fertilizers, no significant problems of pests or disease. The conclusion reached is that biomass can be produced at a cost competitive with fossil fuels under the assumed conditions. ITC arrives at an estimate of slightly more than a dollar per million BTU, and SRI arrives at an estimate of less than a dollar per million BTU as biomass and about $2 per million BTU as a synthetic natural gas. Such costs are quite competitive with fossil fuels prices, but the assumptions made regarding the availability of water in the southwestern US render this scenario somewhat unrealistic. The important economic competition of biomass production is with food production, and it seems that if such favorable growing conditions could be established, the highest value for the crop would be obtained if food were grown rather than energy (89).

Wind Energy

A careful economic analysis of the use of wind energy in electric power network will require the same sort of margin analysis used in the economic analysis of solar thermal plants. Assuming that the maintenance costs of large wind turbines are found to be low, achieving economic feasibility for electric network applications of wind turbines will depend upon a lower capital cost than involved in large (more than 100 kW) machines built in the past.

The large wind turbines built in the past have been primarily experimental devices that were one of a kind, so their capital costs do not provide a good guide as to the costs to be anticipated in widespread utilization. For example, the Smith-Putnam turbine built at Granpa's Knob in the 1940's cost a total of about one million dollars over the life of the experiment for a rated capacity of 1,250 kW, or about $1,000 per kW. At that time the capital cost of fossil fuel plants was about $125 per kW, and fuel prices were low. It was estimated that production models of the Smith-Putnam turbine would have cost $191 per kW, so it did not seem competitive (90,91,57). The 100 kW and 1 MW turbines to be built as part of the ERDA program will provide experience to allow better estimates of the construction costs possible now.

Small-scale applications of wind energy have been widely used and are economic where the costs of obtaining service for electric power networks at remote sites are prohibitive. A variety of small systems for such applications are being marketed, with prices about $5,000 to $8,000 for a 1 kW rated capacity (92).

Ocean Thermal Conversion

Ocean thermal power plants require no storage and provide power at all times (base load) which tends to make their economics more favorable than other solar technologies. However, they also must be constructed to endure the marine environment with little maintenance, so construction costs may be high. In the past, advocates for ocean thermal conversion have estimated the capital cost of large ocean thermal plants would be about \$200 to \$300 per kW, certainly competitive with fossil and nuclear energy (65). Preliminary reports of the more recent analyses by TRW and Lockheed, place the cost of energy from these plants at about 2.7¢ per kWhr in 1985, higher than the previous estimates, but still potentially competitive (71).

THE ENVIRONMENTAL IMPACT OF SOLAR ENERGY

Solar energy is widely touted as being a clean source of energy, and drastic comparisons are offered with fossil and nuclear energy technologies and their environmental impacts. This view is not without some foundation, indeed the authors agree that the environmental impacts of solar energy should be relatively benign. However, the time is long past when we ought to allow any new technology, no matter how innocuous it might appear at first, to be developed and deployed without a careful examination of the possible environmental alterations that might result. We describe here some of the possible deleterious impacts of solar energy technologies, but without any implication that these impacts are more severe than those of the technologies that solar energy might replace.

It is striking how little serious attention has been paid to these possible impacts of solar energy. One reason for this neglect might be that until recently few thought solar energy would ever be a serious alternative to existing energy technologies, but this reason surely no longer holds. We believe a careful examination of the possible environmental impacts of solar energy is now overdue.

Local Impacts

Solar energy facilities will have a certain impact on the local environment of their site, particularly on the heat and water balance of the region. The temperature, the amount of sunlight, and the humidity at the surface of the ground and in the first meter or so above the surface, define a microclimate in which plants, insects, and animals live. These parameters of the microclimate are determined by a number of factors, including the albedo of the surface, the surface roughness which determines the surface wind patterns, and the degree to which the surface is shielded from radiation loss to the night sky (93,94). Solar energy collectors, for either thermal or photovoltaic conversion, which permanently cover a large fraction of the ground, will drastically alter this microclimate, and thus cause major changes in the type of life that can best survive there. Large arrays of wind turbines may have similar effects if they cause significant alteration of surface wind patterns. Solar collectors for heating and cooling of buildings would have a similar effect, except that they will probably be integrated into the buildings, and thus will make only a minor perturbation on the already drastic environmental alterations caused by urbanization and suburban development. Solar heating and cooling of buildings may have an important impact if its use requires widely dispersed buildings in order to avoid shading. Larger land areas would then suffer the impacts of development.

Ocean thermal conversion will have its own special impacts. The operation of the ocean thermal plant will bring up cold waters close to the surface. The most important impact of this will probably not be a change in the temperature of surface waters, though this might occur. The major impact will be the effect on the local ecosystem of the addition, by the cold waters from the depths, of high levels of nutrients not normally present at the surface. The local surface ecosystem will be drastically altered, though this impact might be considered beneficial if it leads to higher productivity of commercial fish (95).

The most drastic of the local impacts of solar energy might be those resulting from the production of biomass for fuels in energy plantations. If previously unused land is employed, then the preexisting natural ecosystem will be replaced with the forced monoculture common in agriculture.

In addition, the energy plantation will be a source of some air pollutants, such as dust, pesticides, and allergenic pollens, and water pollutants, such as fertilizer runoff, pesticides, sediments, and increased salinity (96). These effects are all part of present agricultural practice, and the effect of energy plantations will be to extend them to previously unaffected regions.

Regional Impacts

With the need for regional land use planning becoming more widely recognized, it is important that we understand how the use of solar energy will impact regional land use problems. The most obvious of these impacts is the requirement of the solar facility itself. The amount of land required per unit of energy obtained varies widely among solar energy technologies. A 1,000 MWe solar thermal plant might require as little as 14 Km^2 of collector area (25), while an energy plantation that produces biomass fuel for electrical generation might require as much as 635 Km^2 for the same electrical power output (38).

Water requirements and compatibility with regional supplies must also be considered. Some solar technologies, such as photovoltaic and wind energy conversion might have no need for water, others such as solar thermal conversion might be able to minimize requirements by using dry cooling towers, but bioconversion for fuel production will have significant water requirements that must be included in selecting sites.

Solar energy facilities will cause demographic shifts with important regional consequences. Construction and operation of a solar facility will require a certain additional population, but potentially more important is the industry that might be attracted to a previously undeveloped region by a new and inexhaustable source of energy. With this industry would come residential areas and urbanization. Thus the existence of solar technologies would create strong pressures for development of new areas that are presently wild or used for other purposes.

National Impacts

Any energy facility causes the generation of pollutants at sites throughout the nation because of the diverse industrial activity required for the manufacture and transportation of components for the facility. In assessing the total enrironmental impact of solar energy, we must include in our consideration the entire economic system involved in producing the solar energy facility. Thus, a certain fraction of the pollution generated by a steel plant that, among other things, fabricates supports for solar collectors; a corresponding fraction of the pollution generated by the coal burning plant that supplies the steel plant with electricity; and so on through an infinite chain of industrial activities, must all be included in accounting the pollution released by solar energy (97). Of course, similar considerations apply to all other energy facilities, such as nuclear plants, and with all things considered, solar energy should still be shown to be a very clean energy source.

The material requirements of a solar energy facility, and the impact on the national economy of supplying those materials, should be included among the impacts of the facility. In some cases the requirements for certain materials that would be associated with the widespread deployment of a solar technology are large compared with the present use of that material in the national economy. For example, the amount of gallium required for a 1,000 MWe photovoltaic plant, using gallium arsenide solar cells, would be quite large, indeed, comparable to the estimated national production of gallium from now to the year 2000 (97,98). Even if the solar technology can afford to pay high enough prices to drastically increase production of some needed material, we should not ignore the impact on other segments of the economy of having to match that higher price.

Among the material requirements of solar energy is one of particular importance: energy. A certain energy investment will be required for a solar energy facility for its construction, and it may require a long period of operation to pay back this energy debt. As an extreme example, the energy required to fabricate a 4 cm^2 silicon solar cell by the techniques used in the past has been estimated to be 2.8 kWhr (86) so that about 40 years of operation would be required to regain the energy investment. The energy investment in a solar facility can be minimized by proper design and selection of low energy cost materials (99), but in an accelerated program of solar development, the net energy balance of solar facilities might be negative for a time.

Perhaps the most important among the national economic impacts of solar energy will be problems in providing the high initial investment capital required for solar facilities. Enormous amounts of capital would be required to provide solar facilities rapidly enough to match exponential projections of energy demand. Even the development of practical and economically competitive solar energy technologies will not allow an unrestricted growth in energy use.

Social Impacts

Little attention has been given to the potential social impacts of solar energy utilization. Certainly part of the reason for this is that those developing the technologies have taken as their task the development of one-for-one replacements of existing energy sources. Thus, for example, in solar heating and cooling of buildings, the emphasis is upon development of systems that would be installed by existing building contractors, and would provide to the resident the same thermostat controlled living environment to which he is accustomed. To the resident there would be little or no apparent evidence that the source of energy was solar, rather than gas or electricity. Thus the social impact might be negligible.

However, there are technological options, and ways of applying new technologies, that might have significant social impacts by leading to changes in life styles. For example, the building resident might choose to install a passive solar system to temper, but not control exactly, the living environment of his residence. This is a choice of life style that is at variance with the mainstream of U.S. experience, but might be compatible with the economical use of solar energy.

Technologies, such as solar heating and cooling of buildings, bioproduction of fuels, and wind energy, might allow individuals to establish lives completely independent of the national energy system. There are already movements in this direction, though the number of individuals involved is small. The development of viable energy options that allow independence might serve to further these social movements (92).

It is impossible now to predict what the long term social consequences of solar energy utilization might be, but any technology that becomes as widely used as we expect solar energy to be in the long term, will certainly have a major impact upon our lives and our social institutions.

THE FUTURE UTILIZATION OF SOLAR ENERGY

The Near Term

The present utilization of solar energy in the U.S. is negligibly small. Even if the use of wood for heating is included within this category, present use provides less than half a percent of the nation's energy requirements. The factors that will determine how quickly this situation can be changed include the development of solar energy industries, the progress of the Federal research and development program, and the effect of legislation intended to provide incentives for solar energy and remove institutional barriers to its use.

SOLAR ENERGY INDUSTRIES Within the last few years interested and enterprising individuals have founded a surprisingly large number of small solar energy companies. In addition, a number of large U.S. firms have begun development of prototype solar energy components, in anticipation of a potentially large market. This activity is greatest in the area of heating and cooling of buildings, where a large number of firms now offer components and complete systems (92,100), and in photovoltaic conversion, where the large semiconductor companies have recently begun to explore the possibilities of developing new products (34). The Solar Energy Industries Association was formed in 1974 to aid communication between these industries, and to represent them in matters relating to solar energy legislation at the Federal, state, and local levels (101).

One of the first serious problems to be faced by the solar energy industries is that of maintaining their credibility and reputation. Some solar energy firms have been guilty of making unreasonable claims for the performance and economics of their components and systems for solar heating and cooling. If this practice were to spread unchecked, the credibility of all solar energy firms, and of the technology itself, would be severely damaged. The Solar Energy Industries Association has recognized this hazard and is striving to establish a code of ethical practice for its member firms. Government established performance standards for solar components should also alleviate this problem.

SOLAR ENERGY RESEARCH AND DEVELOPMENT Solar energy R & D programs are underway in many nations other than the U.S., especially Germany, France, Japan, U.S.S.R., and Australia. However, the U.S. program is by far the largest, with a budget in Fiscal Year 1976 of about $140 million.

The U.S. solar energy program, as now formulated, is very aggressive, with a high priority on the earliest possible demonstration of feasibility of each of the approaches to solar energy conversion. A number of these pilot plant and demonstration projects in this program have been referred to previously. They include the heating and cooling of buildings demonstration program, the 10 MWe solar thermal pilot plant, large demonstration arrays of photovoltaic cells, and the 100 kW wind turbine. At the same time, longer range research and development is underway on the technological advances that will be required for the widespread use of solar energy in the longer term (61).

SOLAR ENERGY LEGISLATION Within the U.S., a national commitment to the development and application of solar energy was expressed by the Solar Energy Research, Development, and Demonstration Act (Public Law 93-473) and the Solar Heating and Cooling Demonstration Act (Public Law 93-409). These laws are the basis of the Federal research and development program, and of the heating and cooling demonstration program which seeks to aid the establishment of a solar heating and cooling industry. Further legislation to provide incentives for solar energy has been proposed. This legislation would provide low interest Federal loans for solar heating and cooling systems for residences, or would provide Federal insurance for loans for solar energy systems, thus lowering the interest rates that will be charged by commercial lending institutions.

Legislation has been passed in a number of states, and proposed in many others, to provide incentives for solar energy systems by not including the added value of a solar heating and cooling system in the assessed value of a home, thus lowering the property tax on solar homes.

NEAR TERM IMPACT OF SOLAR ENERGY The feasibility of large-scale utilization of solar energy in the near term, before 1985, is a hotly debated subject. Much of this controversy is a spill-over from the debate over the hazards of nuclear energy, with nuclear critics often proposing an accelerated development of solar energy as an alternative to the growth of the nuclear industry. The authors have no doubt that in the longer term solar energy will serve to reduce significantly the need for other energy sources. However, the possibility of solar energy making a large contribution to the nation's energy requirements before 1985 is small. Reasons for this include the large investment in existing energy systems, the huge capital requirements of a massive introduction of solar energy technology, and the significant technological advances required for solar energy to become competitive economically with the presently important energy sources. These factors will probably keep the contribution of solar energy to the U.S. energy requirements to about 1% of the energy demand in 1985.

The Far Term

Progress in dealing with the technical, economic, and environmental factors discussed in this article will, in our opinion, lead to a "coming of age" of solar energy in the years between 1985 and 2000. We expect that in the period after the year 2000, solar energy will have become one of the conventional energy sources used in many regions of the world. However, attainment of this eventual success will demand patience and a continued dedication to the advancement of solar energy technologies in the intervening years. There is some danger that unrealistic expectations of near term widespread application of solar energy will be suddenly dashed by harsh realities, and that support for the continued development of the technologies might weaken. Such an eventuality would endanger the great contributions that solar energy can make in the longer term if it is given steady and continuous support.

We have described in this article a wide variety of approaches to the utilization of solar energy, and limitations of space have prevented the inclusion of many other promising approaches now under investigation. Many of these approaches will probably not survive to the point of deployment and widespread utilization, but a number will be selected as each being best for a particular energy demand, and included in future energy systems that will draw upon inexhaustible sources of energy.

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