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## NEW TECHNOLOGIES IN SOLAR ENERGY CONVERSION - AN OVERVIEW

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### ABSTRACT

Useful sources of solar energy, besides the direct rays of the sun, include energy stored in the oceans, the winds, elevated waters and biological materials. Systems for putting any of these forms of solar energy to work for us require economical means for 1) energy conversion 2) energy storage and 3) the concentration of energy in space and time to deliver the necessary sustained high power levels required for significant and productive end use. Technological challenges exist in all three of these areas of need. In this paper the authors describe some of the specific needs and review the status of technology in five developing areas of solar conversion: solar thermal, photovoltaic, ocean thermal gradient, wind and the generation of fuels.

### INTRODUCTION

The earth intercepts enough energy from the sun that all man's energy requirements could be met without disturbing the natural forces driven by solar energy. (1,2) However, this energy is so distributed in space and time that it must be greatly concentrated before there is enough to produce the large amounts of work required to drive a mechanized society.

Solar energy is available not only in the direct radiation that is converted to thermal energy as it is absorbed in various materials, but it is found in natural short term collection, concentration, conversion and storage mechanisms; the winds, elevated waters, plant growth, and in the oceans. The first three sources have been exploited beneficially for centuries, but the utilization of energy stored in the oceans remains as one of the great challenges to our ingenuity and technology.

Solar-derived energy is stored in other natural systems, but either too dilutely, too unpredictably or too unmanageably for any anticipated use in solving our energy problems. For example, the atmosphere stores energy electrically but the energy can suddenly be so concentrated that it destroys the equipment and even the people devoted to taming it. Another example is the energy released by the mixing of fresh water from rivers with salty ocean water. While considerable energy is present, no practical means for extracting it is known.

Rather than discuss the more remote energy

possibilities in this paper, only the methods will be reviewed which show promise for meeting the growing energy needs of the next 30 years.

### SOLAR ENERGY SYSTEM REQUIREMENTS

To productively capture and use solar energy requires three processes:

- Conversion
- Storage
- Concentration

No essential order exists for these ingredients, but they are all part of a successful system; some conceptual systems do not have storage, but their applications are limited because of it. For example, photosynthetic processes use sunlight to convert carbon dioxide and water into organic compounds which release energy at a high rate when burned. Thus, the energy is first converted and stored as chemical energy and then concentrated during the passage of time and by the harvesting operation. The heat generated in the burning may be converted to mechanical energy in one of a number of heat engines.

In man-made systems the sun's rays may be concentrated optically (spatial concentration) to produce extremely high power densities. The optical energy is converted to thermal energy by absorption in materials, and this thermal energy may be stored before conversion to electricity or to mechanical energy. Alternatively, the electrical or mechanical output may be stored in various forms for later applications.

### Conversion

While the means to convert solar energy to mechanical or electrical energy are available, the processes are often inefficient, and in most cases this inefficiency is the result of natural limits in thermodynamic cycles and by properties of materials. No system presently envisioned for solar-electric conversion could operate at more than approximately 15 to 20 percent overall efficiency, and designing for maximum efficiencies does not usually result in the most cost effective system. Figure 1 shows practical paths for conversions from solar energy to electricity and the reasonable efficiencies for these processes to

operate with today.

### Storage

Probably the widest range of technical problems in system design occur in storage subsystems. Methods that can be used for energy storage in conjunction with solar energy systems range from simple to extremely sophisticated, but none compares favorably to liquid fuels. Besides cost considerations, the most important basis for comparison must be energy density per kilogram of storage material or per cubic meter of space occupied.

Storage may take many forms; chemical, thermal, mechanical or electrical, with variations in each category. (3,4,5,6) In fact, the indirect forms of solar energy resources (wind, bio-systems and ocean temperatures) are natural forms of mechanical, chemical and thermal storage, and except for the case of the wind, the energy may be recovered from storage at a time and rate chosen by the user. Figure 2 shows a comparison on a logarithmic scale of the representative density for some familiar and some unusual storage systems, on the basis of thermal or mechanical equivalence. The reader should keep in mind that the thermal energy densities are not directly comparable to mechanical energy storage density because of the thermodynamic losses inherent in the thermal-to-mechanical conversion.

Of course, solar energy applications are not the only places where large scale energy storage is of interest. The electric utilities would welcome a breakthrough that would make low cost, high density and high recovery efficiency available to them for energy storage. Such a storage system could be used to match generated outputs, which are best kept uniform, to a network load which has large variation.

### Concentration

Basic to using solar energy to replace large amounts of fuel is the concentration of the captured energy to provide it in a high density form. Efficient high temperature solar thermal systems generate a high solar flux density by optical concentration, while low temperature systems may heat the transport fluid in a distributed field of collectors, and produce the energy concentration by pumping the heated fluid to a central point. Electrical concentration can be used to collect the energy after the generation of electricity through wires feeding to a central point. No large technical problems hamper the required energy concentration, but rather it is the economic disadvantage of having to cover large areas with mirrors or solar cells, or having to move great volumes of ocean water through heat exchangers. These concentration techniques are inherently costly because of the large capital investments required.

In contrast to the spatial concentration of energy

is the natural process of photosynthesis which concentrates energy over a period of time in plant materials. As compared to solar thermal energy concentration, utilization of the bioconversion processes tend to be more labor intensive than capital intensive, and their overall conversion efficiency is much lower, requiring more extensive land areas for the same power production. For example, to generate an average of 500 MWe, a solar thermal power plant would require about 20 km<sup>2</sup> (7.8 sq. mi.) at 10 percent overall efficiency, while under different climatic conditions, the same power production by burning the products of sugar cane would require about 60 times as much land, using 0.5 percent as the solar capture efficiency of these plants.

### TECHNOLOGY STATUS

Major federal funding in unconventional energy sources is being expended by the U.S. Energy Research and Development Administration (ERDA) in pushing toward demonstrations of practical large-scale systems utilizing existing technologies in solar thermal, photovoltaic, wind, ocean thermal and bioconversion. (7) In Table 1, fiscal year 1975 and 1976 federal funding levels are compared for each of these technologies.

Table 1. Federal Funding of Solar Conversion Research Development and Demonstration (in millions of dollars)

	FY75	FY76
Solar Thermal	13.2	19.3
Photovoltaic	5.0	22.4
Ocean Thermal	1.9	8.1
Wind	5.3	15.1
Bioconversion	2.0	4.5
Total	27.4	69.4

In cooperation with this effort, the Electric Power Research Institute (EPRI) supports projects in technology assessment and impact analysis of these solar conversion systems, as well as related R and D programs. A brief review of each technology and its associated problems is given below.

### Solar Thermal Conversion

System and component design efforts are currently underway leading to the eventual demonstration of solar-thermal electric power generation in a 100 MWe plant. The concept being pursued in the demonstration phase is the central receiver or power tower configuration. Systems based on collecting heat from a large field of individual concentrators will be demonstrated too, but in connection with total energy systems. (8) In the central receiver system the principal mode of concentration is optical, with a field of large heliostats consisting of flat or segmented mirrors directing the sun's rays on or into a boiler at the top of a tower. Design details vary among the

contractors involved, so the full-scale design eventually selected may use several towers or only one, and the heliostats may surround the tower or occupy a smaller sector on the north side. (9, 10, 11)

A system supplying conventional steam turbines with superheated steam provides the most efficient solar thermal conversion technique under study. While several direct thermal-to-electric conversion schemes are known and under test in research laboratories, none can match the Rankine cycle engine for reliability, efficiency and economy.

Developers of solar thermal power systems face some difficult storage problems. Thermal storage providing superheated steam is complex if water is the storage medium and requires high-pressure tanks which are very expensive to build and maintain. Few practical high temperature fluids are available to use instead of water, and reliable systems employing eutectic salts for latent heat storage have not been demonstrated. Storing electricity after generation is not yet a practical answer, either. If it were, utilities would have a solution to their peak-load problem.

The ERDA program for solar thermal demonstration has already begun with the design of a facility to test receiver/boiler prototypes. Full capability in this test facility will be reached by 1978 or 1979 with 5-MW thermal capacity. The first large solar thermal electrical output will be produced by a 10-MWe pilot plant to be completed in the early 1980's. Following this pilot demonstration will be a 100-MWe plant to be in operation by 1990.

Important questions to be answered by this staged demonstration concern boiler designs, thermal transients caused when clouds pass over the heliostat field and turbine operation under variable steam conditions. In addition, many problems regarding the design of large thermal storage systems will probably require solutions before a 100-MWe demonstration plant is completed. High thermodynamic efficiencies will be difficult to achieve for solar thermal power plants because of the scarcity of cooling water in the areas most favorable for sunshine. (12)

### Photovoltaic Conversion

The space program has definitely been the parent to the development of photovoltaic materials. Conversion efficiencies have been demonstrated that approach 20 percent (13) and the physics of the photoelectric process prevent doing much better with any known materials. The biggest hindrance to building large-scale photovoltaic generation systems is the high cost. Solar cells presently cost about \$20 per peak watt or \$20,000 per kilowatt, exclusive of installation, storage and interconnection costs. (1) Allowing for an average output that is 25 percent of peak output, the above cost converts to \$80,000 per average kilowatt, or about 100 times the capital investment that might provide electricity that is competitive with fossil or nuclear fueled generators.

Many efforts are underway to bring about cost reductions. High speed fabrication techniques for the photovoltaic crystals and the employment of concentrating devices to increase incident flux densities offer promise in this area.

Because photovoltaic materials do not operate with high flux concentrations, most or all of the energy concentration is made after conversion. This may pose problems for central station power generation, but it suggests possible advantages in decentralized deployment, for instance on individual homes. (14) With capability for feeding excess energy back into the a-c power grid, home systems with solar cells could possibly supply energy more satisfactorily in a widely distributed system than in a centralized system because of the way the distributed system averages out the area cloudiness over time.

A system using large amounts of photovoltaic generation requires some form of regenerative storage. Pumped hydro storage is a good solution in some parts of the country. More exotic storage and regeneration forms such as superconducting magnetic fields, high energy batteries, super flywheels and hydrogen-oxygen fuel cells are not ready for economical large-scale use. However, researchers in each of these technologies are actively seeking to demonstrate cost-effective means for large energy storage systems.

The bulk of photovoltaic research money from ERDA is being applied to research in methods for low cost production of solar cells and to increase conversion efficiency. EPRI is sponsoring studies of photovoltaic materials to operate from thermal (long-wave radiant) energy.

Preliminary studies have been funded to explore the feasibility of deploying large solar collector or photovoltaic arrays in orbit to greatly increase their time of exposure and the intensity of the incident solar energy. Orbiting stations may receive up to 15 times the energy of terrestrial stations. (15) In these systems it is proposed to transmit the converted solar energy to earth as a microwave beam which is received by a large array of antennas and reconverted to dc or 60 Hz a-c power for distribution. The economics of this plan are not encouraging and the technical difficulties are great, but the potential exists for supplying virtually all of our electric power needs from such a space located solar generating station.

### Ocean Thermal Energy Conversion (OTEC)

A significant part of the ERDA research and development budget in solar energy is being applied to the utilization of the temperature difference between tropical ocean surface waters and the deep cooler water. In this scheme, large floating power plants would use surface water at a temperature of about 25 C to vaporize ammonia and the ammonia vapor in turn to drive large turbines. Colder water, at about 5 C, would be pumped up from depths of 500 to 1000 metres to condense the

ammonia, providing a closed-cycle operation. (16, 17) The principal attraction to this mode of using solar energy lies in the natural collection and storage system that makes the energy available with minimal regard to seasonal and diurnal cycles or weather conditions.

Disadvantages to the utilization of ocean thermal energy occur in the tremendous volumes of water that must be handled and the extremely low conversion efficiency of turbines operating on temperature difference less than 20°C. After allowing for temperature drops in the heat exchange processes and reasonable turbine efficiencies, the system must move about 450 tons of warm water and 450 tons of cold water every minute for each MW of generated output. In the Gulf Stream, ocean currents can be used to aid in driving this large volume of water through heat exchangers. Otherwise, from a system extracting only three to four percent of the available ocean thermal energy, more than one-third of this generated power may be required for moving water through the system.

In separate efforts funded by ERDA, two teams led by aerospace contractors have completed feasibility studies on OTEC. Their reports conclude that OTEC plants offer the potential for economic conversion of ocean temperature differences to electric power after implementation begins on a large scale. Besides delivering electrical output through undersea transmission lines, the energy might be used in energy intensive manufacturing processes in a co-located chemical or industrial plant. Fuels generated on site offer still another possibility for delivering the ocean thermal energy output in a useful form.

Plans of ERDA call for an ocean thermal test facility which may be land or water based for its pilot operation. Their tests would lead to a prototype plant construction in the early 1980's. Research projects are being carried out separately and in parallel with the demonstration programs to study heat exchanger materials and design, bio-fouling problems, and energy transmission methods.

Other ocean sources which man has sought to tap include waves, tides and currents, and even the energy generated by the mixing of saline water with fresh water where rivers join the sea. (18) However, none of these offers the large amount of energy that OTEC potentially can produce.

### Wind Energy Conversion

Utilization of wind energy is, of course, one of the oldest means of putting solar energy to work for mankind. It has the appeal of already being a mechanical form of energy, so conversion to shaft energy is possible at efficiencies approaching 50 percent. However, the problems of concentration and storage make wind energy very difficult to use on a large scale. (19,20)

The energy contained in moving air is proportional to the third power of the air speed, so a 20 m/s wind has eight times the energy content of a

10 m/s wind. Practical windmills follow this dynamic range only within some limits. Typically a rotor may not produce shaft power until a threshold wind speed, say 5 m/s is present. Then the maximum output may be reached at 20 or 30 m/s, and provisions may be made for feathering or other protection when even higher winds are encountered.

Besides large rotors mounted on horizontal shafts, demonstration concepts include vertical shaft types which do not need to follow the wind direction. Unit sizes, limited by the nonlinear costs of large structures, point toward decentralized windpower generation facilities with nominal outputs of approximately 1-MW. At least one concept which can produce a large output from a single generator is under study. In this scheme many sail driven vehicles linked together move around an oval track, coupling their energy into a generator shaft at some point along the track.

Like the sun, the wind is not a constant source of energy, so storage must be considered when a practical system is designed. Suitable techniques for storing the energy output of wind-driven generators are the same as those considered for photovoltaic systems; flywheels, superconductors, batteries or generating chemical products for operating fuel cells.

A 100-KW windmill has recently been built by NASA Lewis Research Center at a site near Sandusky, Ohio. This and other demonstration configurations will be tested and the results used to aid in the design of units rated for megawatt output. Concurrent research activities, besides addressing the storage problem, involve location, spacing, and interfacing questions.

### Bioconversion

In using solar energy to drive chemical reactions that generate organic fuels, natural processes are still better than any that man has devised. Even so, the best overall efficiency for conversion of sunlight to plant matter by photosynthesis is well below one percent. (21) Conversion of plant and animal products to gaseous or liquid fuels may be accomplished with little loss in the stored energy. In view of the low overall efficiency involved, it is unlikely that the known natural processes will ever supply the fuel required by even the country's present transportation system. As a point of reference, farming operations in the U.S. are presently estimated to consume five or six units of energy for every unit of energy in the food delivered to market. This leaves some distance to go before energy farming is practical.

Bioconversion as an application of solar energy may be used at several levels of sophistication. (22) The simplest concept is to grow plant materials, dry them and use them for fuel. Related to this is the direct burning of trash and waste for the energy content.

In the next level of bioconversion systems, the organic materials, either freshly grown or as

waste products, are changed chemically to produce liquid or gaseous fuels. At present, the best processes for producing these chemical changes are:

1. Pyrolysis in which high temperatures are used in the absence of oxygen to break the chemical bonds of organic materials and release methane, hydrogen and various liquids.
2. Anaerobic digestion or the use of bacteria which operate in the absence of oxygen to break down the carbohydrates from plant and animal materials in a multistaged process to yield methane, carbon dioxide and other gases.
3. Fermentation; the enzymatic decomposition of sugar molecules into alcohol.

At the highest level of sophistication in bioconversion systems are the photochemical reactions which are often aided by catalysts and used for the direct production of a fuel. (21,23) Several means are under investigation to produce hydrogen by the photodissociation of water. Other even more complex reactions that produce hydrogen are possible using plant cells and sunlight in photosynthetic operations. Others yield free electrons, thereby acting as an organic photocell. (21)

One large aerospace firm is experimenting with a multistaged thermochemical process to produce hydrogen. The thermal energy that is available in burning the hydrogen is estimated to be about 50 percent of the thermal input used to drive the process. This is a very satisfactory efficiency for thermochemical storage. However, for ease of storage, the products of an ideal thermochemical storage system should be liquid at moderate temperatures and pressures.

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### Illustrations

Figure 1. Solar-electric conversion processes and efficiencies (percent).

Figure 2. Preliminary estimates of energy density for storage in various media.

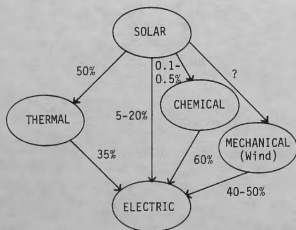


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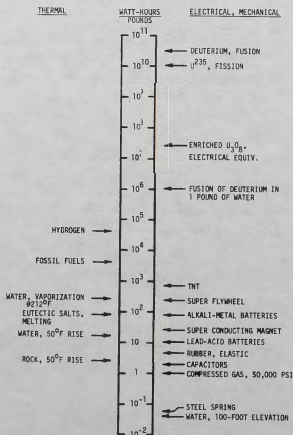


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