**Solar Energy as an Alternate Energy
Source to Mixed Oxide Fuels in
Light-Water Cooled Reactors**

H. W. Bertini

**Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
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SOLAR ENERGY AS AN ALTERNATE ENERGY SOURCE TO MIXED OXIDE
FUELS IN LIGHT-WATER COOLED REACTORS

H. W. Bertini

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29

Table of Contents

	<u>Page</u>
ACKNOWLEDGMENTS	v
ABSTRACT	1
INTRODUCTION	1
BRIEF DESCRIPTIONS OF THE VARIOUS SOLAR SYSTEMS	2
Heating and Cooling	2
Process Heat	4
Solar Electric Systems	9
Solar thermal (central receiver)	9
Solar thermal (distributed collector)	9
Photovoltaic cells	14
Wind energy	14
Ocean thermal conversion	17
Fuels from Organic Materials	19
PROJECTED SOLAR ENERGY UTILIZATION IN THE YEAR 2000	19
POTENTIAL SOLAR SUBSTITUTION FOR BASE LOAD LWR's	24
Capacity Displacement	24
Economic Considerations	27
Effect of recycling option on solar economics	27
Projected solar costs	28
LAND USE OF SOLAR VS NUCLEAR	29
Solar Thermal (Central Receiver)	30
Photovoltaic	31
Windmills	31
RELATED SUBJECTS ON SOLAR ENERGY	33
Technical Problems	33
Heating and cooling	33
Process heat	33
Solar thermal conversion to electricity	33
Photovoltaic	33
Wind energy	34
Ocean thermal	34
Environmental Problems	34

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	<u>Page</u>
Social and Institutional Problems	35
CONCLUSION	35
APPENDIX	36
REFERENCES	39

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ABSTRACT

Supplemental information pertaining to the generic environmental impact statement on the Pu recycling process for mixed oxide light-water cooled reactors (GESMO) was requested from several sources. In particular, the role of alternate sources of energy were to be explored and the implications of these alternate sources to the question of Pu recycle in LWR's were to be investigated. In this vein, solar energy as an alternate source is the main subject of this report, along with other information related to solar energy. The general conclusion is that solar energy should have little effect on the decisions concerning GESMO.

INTRODUCTION

In the generic environmental impact statement on the use of recycled plutonium for mixed oxide fuels in light-water cooled reactors (GESMO), the assumption is made that the number of light-water cooled reactors (LWR's) in operation by the year 2000 will be independent of the choice of fuel cycle option.¹ Questions raised by the hearing board on GESMO regarding this assumption point to the possibility that the number of LWR's might decrease if Pu recycle is not permitted.² A corollary question for impact statement purposes is, could this decrease in the number of reactors be offset by alternate sources of energy. This study is directed toward that question and to other related questions when solar energy is taken as the alternate energy source, and the study also includes general information pertinent to solar energy as a resource.

As a basis for comparison, the decrease in the nuclear capacity by the year 2000, due to a negative decision on Pu recycle, will be assumed to amount to 5, 10, and 20% of the nuclear capacity which is presently

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projected for that time and which was assumed to be independent of the fuel-cycle option utilized. The nuclear capacity in the year 2000 is estimated to be 507,000 MW(e),³ therefore the decrease in nuclear capacity will be taken as 25,350; 50,700; or 101,400 MW(e).

BRIEF DESCRIPTION OF THE VARIOUS SOLAR SYSTEMS

There is sufficient energy in the insolation from the sun to supply all of the present United States energy needs even if only a small fraction of the United States land area is utilized for the capture of the sun's radiation.⁴ The two major problems with solar energy as a resource are that it is diffuse and it is intermittent. Large collector areas are required because of the diffuseness, and the intermittency causes problems because the energy is not readily available on demand. Some of the ramifications of these shortcomings are discussed in subsequent sections. Figure 1 shows the average distribution of insolation over the United States.⁵ Various systems that would utilize the energy from the sun have been proposed and they will be described briefly in general terms.

Heating and Cooling

Systems designed to heat and cool buildings have been proposed and some have been constructed. A common type is a flat plate collector which consists of a pair of closely spaced flat metal plates, welded on the sides with headers at each end. A liquid, which can be water or a solution of antifreeze, passes through the headers and flows between the metal plates. The upper surface of the metal plate is coated with a blackened material to absorb the sun's rays, and the plates are boxed with insulation on the bottom and with one or two transparent glass plates or other suitable material on the top. The functions of the plates are to utilize the greenhouse effect, to reduce heat losses from convection, and to protect the blackened metal surfaces. This boxed collector is placed on the south-facing roof or walls of the building.

Fig. 1. Distribution of solar energy over the United States.^a

^a Figures give solar heat in Btu/ft² per average day.

The liquid is pumped from a storage tank through the collector where it picks up heat and then flows back to the storage tank. The heated liquid in the tank serves as a source of heat for the heating and cooling requirements of the building. The collector and storage tank are shown in Fig. 2, and a schematic diagram of the entire system is illustrated in Fig. 3.

Temperatures attainable by simple flat plate collectors $\sim 90^{\circ}\text{C}$ ($\sim 190^{\circ}\text{F}$) are adequate for heating but generally inadequate for cooling. The temperatures required for common LiBr air conditioners are $\sim 120^{\circ}\text{C}$ ($\sim 250^{\circ}\text{F}$). Various schemes have been studied to raise the temperature such as utilizing concentrators of the sun's rays and substituting selective absorbers in place of the blackened surface. The concentrators focus the sun's rays and have the disadvantage of utilizing only the direct rays from the sun. The diffuse component of the insolation cannot be used. They must also track the sun which adds to the complexity of the system. The selective absorbers capture both the diffuse and direct radiation, and they are designed to be highly absorptive in the peak region of the incident solar spectrum and highly reflective in the much longer wave length region of the spectrum emitted by the heated collector. This is shown in Fig. 4, and the layers of two sample selective absorbers are shown in Fig. 5 (not to scale).

Research, development and demonstration (RD&D) for the heating and cooling of buildings is proceeding at a moderate pace.

Process Heat

The term process heat refers to the generally low-temperature hot air and hot water requirements for industry and agriculture. Flat plate collectors have been studied for their application in this area.

Another approach is the use of solar ponds, which are shallow trenches dug in the earth. The trenches are made impervious to water leakage by coating their inner surfaces with tar, and they are covered with one or two transparent plastic sheets. The trenches are filled with plain water or a saline solution, and they are connected to a hot

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Fig. 2. Collector and Storage Tank.

Fig. 3. Schematic of residential heating and cooling with solar energy - one alternative.

Fig. 4. Spectra of incoming solar radiation and thermal reradiation from a heated surface. A selective coating captures the energy in sunlight by having a high absorptivity to visible light but a low emissivity (high reflectivity) to infrared light.

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$$\left(\begin{array}{l} 1\mu = 10^{-4} \text{ cm} \\ 1\text{\AA} = 10^{-8} \text{ cm} \end{array} \right)$$

SiO ₂	~ 10 μ
Si	~ 10-100 μ
SiN (BUFFER)	~ 500 μ
Au (OPAQUE)	~ 10 μ
METAL OF COLLECTOR ~ 3000 μ	
— WATER —→	
BULK ABSORBER	

Al ₂ O ₃	~ 50 $\text{\AA}$
Mo	~ 50 $\text{\AA}$
Al ₂ O ₃	~ 600 $\text{\AA}$
Mo	~ 800 $\text{\AA}$
METAL OF COLLECTOR ~ 3x10 ⁷ $\text{\AA}$	
— WATER —→	
INTERFERENCE FILM ABSORBER	

Fig. 5. Examples of selective absorbers.

water storage tank, which serves as the source of process heat. The radiation from the sun passes through the plastic sheets and is absorbed by the liquid in the trench or by the tar coatings on the inner trench surfaces, thus heating the liquid.

The simplicity of this approach is offset by the cost of the land which must be available for the trenches.

Solar Electric Systems

Solar Thermal (Central Receiver)

This, and the system described next, is designed as a central-station electric power plant. Each system is designed to replace the boiler in a relatively standard central station electric power plant. The components of such a power plant are illustrated schematically in Fig. 6. The central receiver system consists of a vast field of heliostats, located at ground level, that reflect the rays from the sun into the bottom of a boiler which is perched on a high tower. The individual heliostats are servo-controlled to track the sun. One concept⁶ of such a system is illustrated in Fig. 7, and a sectional view of a boiler is shown in Fig. 8. The technical problems associated with these systems are described in a subsequent section.

The central receiver has a relative advantage over the distributed collector (described next) in that higher temperatures can be attained. A 5 MW(e) demonstration plant is under construction at Sandia, New Mexico.

Solar Thermal (Distributed Collector)

The distributed collector system differs from the central receiver in that all components are at ground level and an alternate focusing method is used. The system consists of individual parabolic-shaped troughs that reflect the rays of the sun onto a pipe located at the focal point of the parabola. The pipe carries the fluid which is heated as it passes through. The individual collectors must be servo-controlled to track the sun. One approach⁷ is illustrated in Fig. 9.

Fig. 6. Schematic diagram of a typical central-station electric-power plant.

PHOTO 2424-77

Fig. 7. Artist's concept, 10 MW(e) central receiver solar thermal pilot power plant.

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Fig. 8. Optical cavity absorber.

Fig. 9. Parabolic trough collector with heat pipe and steam generator.

In general, the temperatures attainable by these systems are lower than those in the central receiver, and hence the collector field must be larger to produce the same power. The priority given to the RD&D of these systems is lower than that for central receivers.

Photovoltaic Cells

A photovoltaic cell is a solid-state converter of light to electricity. They were utilized extensively in the space program to provide electricity to both manned and unmanned satellites. When a photon from the sun is absorbed by a photovoltaic cell, the photon creates a free electron and a "hole" in the normal electron sea that exists in the cell. The cell is so constructed that the manufactured inhomogeneities, which were introduced in the crystal-cell structure, create a small electromotive force that drives the free electron and hole in opposite directions. With sun shining on it, the cell can thus produce electricity. Arrays of such cells placed on south-facing roofs or walls of buildings are envisioned to produce electricity for the buildings, and vast arrays are under consideration for the central-station generation of electricity.⁸ Figure 10 shows a conceptual design of a 100-MW(e) photovoltaic power plant.

The maximum theoretical efficiency of photovoltaic cells is ~20%, and they are currently manufactured at ~10% efficiency. The cost of these cells, \$20 - \$30,000 per peak kW (or about \$100 - \$150,000 per average kW) is at least a factor of 100 to 150 times too high to be competitive. New methods in the manufacture of the cells by growing single crystals in continuous ribbons are under development. Innovative manufacturing techniques such as this are required to reduce the cost of the cells to competitive levels.

Wind Energy

The old concept of the windmill is being renovated in attempts to capture the energy that is available in the wind. A windmill of modern design is shown in Fig. 11.

Fig. 10. 100 MW(e)* photovoltaic power plant.

*Average daytime.

Fig. 11. Typical wind rotor system.

The energy available from the winds that blow over the United States is significant, and if all of it were utilized it could presumably have supplied all of our electrical energy needs in 1973.⁹ This estimate is considerably higher than most others, as will be discussed in a following section, but if we are striving for independence of imported fuels then the size of the wind-energy resource is sufficiently substantial to warrant RD&D.

The average capacity factors that result from the intermittency of the wind vary from about 0.6 to 0.7 in the great plains to about 0.4 in various areas of the West Coast and about 0.4 to 0.7 on the East Coast. Currently, designed windmills reach their rated power in winds of 15 - 25 mph.

A demonstration 100-kW(e) wind machine has been constructed in Plum Brook, Ohio, with blades that are 125 ft in diameter.

There are plans to construct several other demonstration machines of increasing power before the end of the decade with the machine of maximum power rated between 1 - 3 MW(e).

Ocean Thermal Conversion

There is a temperature difference of $\sim 20^{\circ}\text{C}$ ($\sim 40^{\circ}\text{F}$) between the warm surface waters of the ocean in the equatorial regions of the earth and the deep ocean water. This temperature difference can be utilized to generate electricity. The suitable conditions of warm surface water and cold ocean bottom exist in the Gulf Stream in proximity to the Coast of Florida, and so this potential resource is available to the United States. A conceptual design of such a system is shown in Fig. 12.

Because the available temperature difference is so small these systems must be enormous in order to generate power of any significance. Furthermore, tremendous quantities of warm and cold water must be pumped through the system to produce significant power, and the power used to operate the water pumps represents a substantial fraction ($\sim 15\%$) of the rated power of the system.¹⁰ The technical problems associated with these systems are discussed in a subsequent section. The ERDA R&D funding for ocean thermal systems represents about 10% of their total funding for solar electric applications.

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Fig. 12. An artist's impression of a solar power plant utilizing the thermal gradient of tropical oceans. Water at 25°C would be taken in at the top and water at 5°C would be taken in at the bottom. The difference in temperatures could be used to drive a turbine. The entire device would be neutrally buoyant in several hundred feet of water.

Fuels from Organic Materials

The object of the organic materials program is to convert organic materials to useful fuels. The organic materials can be crops, such as sugar cane and suitable trees, or agricultural wastes (manure) and municipal wastes (garbage and sewerage).

There are three approaches under investigation. The first is hydrogenation and it applies to crops. It involves heating the organic material with CO and steam to about 300°C (570°F) under high pressure (~100 - 250 atm). The product is a fairly heavy oil. The second approach is pyrolysis where the feed material (again crops) is heated at atmospheric pressure to high temperatures [~500°C (~930°F)] in an oxygen free atmosphere. The products are oil, a low heat-content gas, and combustible char. The third approach is bio-conversion where the feed material, which can be either waste products or crops, is fermented through bacterial action producing a sludge and useful gases, i.e., methane. This approach is utilized by several cities as a method of waste disposal. R&D in this area is funded at about half of the level of that for ocean thermal conversion.

PROJECTED SOLAR ENERGY UTILIZATION IN THE YEAR 2000

There is considerable variation in the estimates of the contribution that solar energy might make to our energy needs in the year 2000. Several of the more optimistic projections are given in Table I. It should be pointed out that in all but one of these studies various scenarios were selected in order to achieve the values quoted in the Table. These values were established as goals so that the United States dependence on imported fuels could be reduced or eliminated. Only one attempt was made to evaluate the likelihood of achieving these goals.¹¹ Other groups and solar energy experts have more pessimistic opinions of the extent to which solar energy will be utilized in the next 25 years. These opinions will be described below.

Rather than attempt an evaluation of the reasonableness of each prediction, for the purposes of this report all predictions were given equal weight and a simple average for each system was calculated. These averages are shown in Table I. The average values of the estimated contributions are summarized in Table II along with the fractions of the estimated energy needs for the year 2000 that they represent. The results indicated that under optimistic assumptions, solar energy utilization might supply about 7% of the total United States energy needs for the year 2000, and represent about 10% of the total electrical energy capacity for the same year.* However, some of the United States pioneers in the field of solar energy express caution with respect to the expectation of the implementation of solar energy systems. H. C. Hottel of the Massachusetts Institute of Technology, whose involvement in solar energy research spans a period of over 35 years, states,²⁴

"The sun can possibly supply low potential energy for domestic hot water, house heating, and air conditioning but the effect on the national energy balance cannot but be insignificant for decades. Solar energy as a source of power has poor prospects of economic significance until the distant future when fossil fuel supplies are several times, and nuclear fuel supplies many times more expensive than at present [1973]."

And George Löf of Colorado State University, who is another well known proponent of solar energy systems and who has, in fact, constructed a solar heated warm air system for his home, states,²⁵ (in testimony before the House Committee on Science and Astronautics),

"This committee has heard testimony related to the status and prospects of solar power plants and can therefore appreciate the formidable technical and economic barriers to that application in the near future. In spite of some optimistic claims by enthusiastic proponents of various schemes for solar power generation, objective analysis shows that electricity from solar energy will cost at least several times the current [1973] cost of conventional power."

*This does not mean that solar energy might displace 10% of the total electrical generating capacity. See the next section for a detailed discussion of this point.

Table I. Estimated Solar Energy Installed Capacity for the Year 2000

Method of supply	Estimated capacity	Average of the estimated capacities	Reference
Heating and cooling of buildings	3.5 quads ^a		12
	2.0 ^b		13
	5.9 ^b		14
	3.6 ^c		15
	3.3 ^d		16
		3.7 quads	
Process heat	1.0 quads ^e		13
	1.8		15
		1.4 quads	
Thermal conversion to electricity	28 [$\times 10^3$ MW(e)] ^f		17
	20		13
	84 ^g		15
	11		18
		36 $\times 10^3$ MW(e)	
Photovoltaic	45 [$\times 10^3$ MW(e)] ^f		17
	30		13
	84 ^g		15
	12		19
		43 $\times 10^3$ MW(e)	
Wind energy	28 [$\times 10^3$ MW(e)] ^f		17
	20		13
	80 ^h		15
		76 $\times 10^3$ MW(e)	
Ocean thermal conversion	18 [$\times 10^3$ MW(e)] ^f		17
	10		13
	72 ⁱ		15
		33 $\times 10^3$ MW(e)	
Organic materials	3.5 quads ^f		20
	3		13
	13		15
		6.5 quads	

^a1 quad = 10^{15} Btu.

^bRepresents the maximum impact of any scenario considered in ERDA-48 (Ref. 12).

^cReference 15 reports a value of 2% of the total U.S. energy requirements for the year 2000, but the total estimated energy requirements in Ref. 15 is 180 quads for the year 2000, which is higher than the estimated 163 quads in Ref. 21, and also higher than 150 quads which is a calculated extrapolation to the year 2000 (assuming a 2.8% growth rate) from the data in Ref. 22.

^dCalculated from the estimated 2% of the nation's energy requirements for the year 2000. This number was taken to be 163 quads (Ref. 21).

^eThe sum of agricultural and industrial applications.

^fThe average of the range of values quoted.

^gAverage of the 2 to 5% of the total energy requirements shown in Ref. 15 (6×10^{12} watts). A 40% thermal to electrical efficiency was used to calculate the power-generation capacity by an equivalent fossil-fuel plant, i.e., the tabulated figure [84×10^3 MW(e)] = $[(.02 + .05)/2] \times 5 \times 10^{12}$ watts $\times 0.4$.

^hAverage of the 5 to 10% of the total energy requirements shown in Ref. 9. Calculation similar to that in footnote g.

ⁱAverage of 1 to 5% quoted in Ref. 15. Value shown in Table I calculated as in footnote g.

Table II. Fraction of total estimated U.S. energy requirements for the year 2000 that might be supplied by solar energy based on averages from Table I

Method of supply	Average of estimated capacities	Percentage of U. S. requirements ^a
Heating and cooling of buildings	3.7 quads	
Process heat	1.4	
Organic materials	6.5	
TOTAL	11.6 quads	7%
Thermal conversion to electricity	36×10^3 MW(e)	
Photovoltaic	43	
Wind energy	76	
Ocean thermal	33	
TOTAL	188×10^3 MW(e)	10%

^aTotal energy requirements for the year 2000 were taken to be 163 quads (Ref. 21), and the total electrical generating capacity for the year 2000 was taken to be 1887×10^3 MW(e) (Ref. 23).

Although solar energy has the potential for supplying all of our energy needs, even the optimistic data in Table II indicate that for the mid-term (~2000 A.D.) at least, other resources must be considered.

The data are termed optimistic because it has been tacitly assumed that all of the technological, economic, and institutional problems associated with these systems will be solved early in the time span under consideration. They must be solved early in the time span so that the remaining time can be used for the massive implementation of these systems that is required in order to fulfill the expectations indicated in Table II.

Furthermore, the solar contributions as viewed by two major federal agencies which are concerned with energy supply have not been included. These agencies are the Department of the Interior and the Federal Energy Administration. Quoting from the former (Ref. 21, p.25),

"The role of solar energy in supplementing other energy sources was difficult to evaluate. *It was felt that solar energy would not, barring a major technological breakthrough, play any significant role in the production of electricity.* (Italics added). However, the household and commercial sectors may, in the immediate range, successfully exploit solar energy. As solar heating and cooling are capital intensive, government subsidization of solar homes, and the industry to support this effort, may become necessary. The role solar energy will play in the context of future energy consumption is so dependent on government policy that forecasting its future use was not feasible."

Quoting from the latter (Ref. 22., p. xxxiii),

"Solar, geothermal, and synthetic fuels will make only a small contribution to the domestic energy supplies by 1985 (about 1%)."

"The major contribution from solar, geothermal, and synthetic fuels will not be felt until after 1990."

"Unless commercial size plants are started now and proven economic by 1985, it will not be possible for these new sources to replace dwindling supplies of oil and gas in the post-1985 period."

In the same reference the total projected contribution from solar, geothermal and synthetic fuel in the year 1990 for a reference scenario is (2 quads out of a total of approximately 120, Ref. 11) about 1.7%, and for an "under-most-optimistic-conditions" scenario the prediction is approximately 6 quads or about 5%.

In summary, most reports conclude that the most likely candidates, among the family of solar systems, to make an impact on our energy needs by the year 2000 are those pertaining to space heating and cooling and to organic materials. There is such a great diversity of opinion on the potential impact of the other solar systems that it would be unwise to reject proven systems by relying heavily on the anticipated success of the solar systems in question.

POTENTIAL SOLAR SUBSTITUTION FOR BASE LOAD LWR's

Capacity Displacement

There is a possibility that if the recycling of mixed oxide fuels is not permitted the projected electrical generating capacity of light water reactors in the year 2000 may have been overestimated. The question to be answered for the impact statement purposes of the recycling process is, could this potential decrease in nuclear capacity be replaced with solar systems by the year 2000.

Essentially all of the solar systems that rely on direct conversion of the sun's rays, and also including wind systems, are designed to date with limited storage capabilities. Put another way, heating and cooling systems, process heat, systems involving conversion to electricity by central receivers, distributed collectors, photovoltaic cells, and wind as presently designed have no long term storage capabilities. In this context "long term" storage means a storage system of such capacity that auxiliary systems or standby conventional electrical systems are not needed. Nuclear systems as well as fossil fueled systems are assumed to be conventional.

All of the solar systems conserve fuel when they are in operation, but when there has been no sunshine or wind for a sufficient period of time auxiliary heaters for space heating and cooling, and standby

electrical generating systems must be turned on. These solar systems then have not displaced conventional capacity, since the capacity must be available at the time that the limited storage capabilities of the solar systems have been depleted.

There are two ways that capacity can be displaced. One is the invention and utilization of a long term energy-storage system. The other is the installation of a relatively large number of solar systems at diverse locations. This number and diversity must be large enough so that there would be a high probability that at least some of the systems could be in operation at any time. Detailed calculations to determine the minimum numbers and the combinations of solar and wind systems that could displace conventional capacity have not been carried out. In fact, the data necessary for such calculations are only now being processed.²⁶ A very approximate calculation (Appendix) indicates that for a system consisting of 100 MW(e) capacity from solar energy in combination with 20 MW(e) of capacity from wind, and with both solar and wind units dispersed over the entire United States there would be a 97 to 99% probability that 10 MW(e) would be available to the U.S. system at any time. Hence, 10 MW(e) of conventional capacity might be displaced for the proposed system, but the implication of this displacement is, for example in an extreme case, that power generated on the west coast would be readily available on the east coast if needed. The value of the failure-to-meet-demand quoted by industry is one day out of ten years, or a systems reliability of 99.96%.²⁷ The figures from the approximate calculation are presented only to give an idea of the relatively small leverage that even widely dispersed solar systems would have on capacity displacement, and they are not meant to provide information upon which reasonable judgments can be based. Such judgments can be made only after the necessary data are available and the detailed calculations carried out.

Another point to be made is that a study by the Aerospace Corporation indicates that the operation of central receiver solar energy plants could be more competitive (compared to conventional plants) if they were intended to supply intermediate load electricity.²⁸ They would be far less competitive for base load or peak load applications. This study indicates therefore, that even if solar central station power plants are

employed, it is more likely, on the basis of economic considerations, that they would be used to supply intermediate load electricity and they would not likely supplant LWR's, which supply base load power. The likelihood that an economically feasible long-term storage system will be invented in time to be useful is completely uncertain. Sufficient to say that the funding for research in storage systems is not considered part of the ERDA solar energy program at the present time.

Of the two remaining solar systems not discussed above, i.e., ocean thermal systems and organic materials, the latter will not displace conventional capacity, because one of its primary objectives is the production of fuel. The other objective is the disposal of wastes.

Ocean thermal conversion, then, is the only solar system remaining that could directly displace conventional capacity. Using the average value of the optimistic projections of Table I [33×10^3 MW(e)], ocean thermal systems might displace approximately 7% of the anticipated nuclear capacity [507×10^3 MW(e)] by the year 2000. However, it is anticipated that ocean thermal electric systems will also be applied to processes other than the production of base load electricity. These are the production of hydrogen, ammonia for fertilizers, aluminum, and/or other energy intensive products.^{29,30} If such applications are realized, the predicted capacity displacement would be reduced.

There are many serious technological problems that must be overcome before large scale utilization of ocean thermal systems can occur. These problems are described in a subsequent section. Since research and development on these systems is only now being undertaken, it would not seem prudent to rely on the large scale implementation of these systems to replace the capacity of systems already proven.

To summarize, because of the intermittency of the sun and wind and in the absence of a long-term energy-storage system, all of the solar systems under discussion except one require standby capacity of a size equal to the size of the solar system. Each individual system thus saves fuel but does not replace conventional capacity. A mixture of dispersed solar systems might replace some capacity, but the ratio of capacity displaced to total solar system size is small. Reliable quantitative estimates of this ratio must await the accumulation of the pertinent

weather data and the performance of detailed calculations. Indications are that solar central station power plants are most economic is applied to intermediate load electricity, and hence they are not likely to replace base load LWR's. On a relative scale, funding for R&D in energy storage systems is small, hence major breakthroughs in this area are not likely. Such a breakthrough would be required for the individual solar systems to replace conventional capacity. The ocean thermal system is the only solar system that relies on a stable source of energy, i.e., the temperature difference between surface and deep ocean water, and it is the only one that could displace conventional capacity without storage. Optimistic estimates of the installed capacity of these systems by the year 2000 represent 7% of the estimated nuclear capacity for that year. However, the anticipated use of these plants includes the production of energy intensive products in addition to the production of electricity, and hence the 7% is an overestimate of the capacity displacement. In order to fulfill the 7% requirement thirty-three 1000 MW(e) plants must be built offshore in the next 25 years. Considering the fact that there are many unresolved problems associated with these systems, which are just now receiving attention, it does not appear prudent to rely on the displacement of conventional capacity by these systems.

In conclusion, it appears unlikely that solar energy will displace even as much as 5% of the anticipated nuclear capacity by the year 2000.

Economic Considerations

Effect of recycling option on solar economics

The discussion in this section will be restricted to economics alone, and the subject that will be explored is the following: the cost of electricity consists of three separate parts, the principal and interest charges on the capital investment, the operation and maintenance charges, and the cost of fuel. The sum of these costs over a one year period divided by the electrical energy delivered during the year is the cost per kWh of the electricity. Solar systems do not burn fuel, and so the cost of electricity from these systems consists of only the first two of the

three components. Given some assumed price of electricity, it is a simple matter to work backwards and calculate the capital investment of the solar system that would be required to produce electricity at that price. The capital cost of the solar system is therefore established as a competitive target by the cost of the electricity which is produced by conventional means.

It is pertinent to the generic impact statement for the Pu recycling process to estimate the impact that recycling may have on this competitive target capital cost of solar systems.

The difference in electrical energy costs with and without Pu recycling is estimated to be 0.5 mills/kWh.³¹ The capacity factor for solar systems is assumed to be the same as that for LWR's,³² namely 0.65, and the fixed charge rate on the capital investment is taken to be 15.5%, and the annual operating and maintenance charges are taken as 1.5% of the capital investment. Then the difference in the target capital costs, ΔC , for solar systems if they are to be competitive with LWR's with and without recycling is calculated to be

$$\Delta C = \frac{0.5 \text{ mills/kWh} \times .65 \times 8760 \text{ hrs/yr} \times 10^{-3} \text{ \$/mill}}{(.155 + .015)/\text{yr}} \approx 17\$/\text{kW}$$

Estimates of the capital costs of solar systems vary considerably. For example, in one study³³ the cost varied from 2150\$/kW(e) to 1730\$/kW(e) depending on the receiver, while in another³⁴ the cost was 1223\$/kW with a somewhat different receiver.

In conclusion, the small difference in the cost of generating electricity with and without Pu recycle will make an insignificant difference in the target costs for solar energy systems in order that they be competitive.

Projected Solar Costs

At the present time, the primary obstacle to the large scale utilization of solar energy is the cost of the systems, for there are no fundamental unanswered questions concerning their ability to operate. An

exception to this is the biomass process, because in many locations this process can compete with present methods of waste disposal (land fills). A study of the projected costs of solar systems vs conventional systems was carried out by the Mitre Corporation,³⁵ and the results are summarized in terms of an Economic Viability Ratio. This is defined as the ratio of the total annual costs of typical solar energy systems to corresponding conventional systems using fossil fuels. The results of their study are shown in Table III projected to the year 2000.

Inherent in these projections is the assumption that the major known problems and potential problems associated with the technology of these systems will have been favorably resolved.

Table III. Projected economic viability ratio
(solar/conventional)

	1985	2000
Heating and cooling	1 to 1.5	1 to 1.25
Process heat	1.5 to 2	1 to 1.5
Solar-thermal	2.5 to 3	2 to 2.5
Ocean thermal	1 to 1.5	1 to 1.25
Photovoltaic	6 to >10	1 to 4
Wind	~1	~1
Organic materials	~1	~1

LAND USE OF SOLAR VS NUCLEAR

The unit of land-use that will be utilized for the comparison of the land used by solar vs that used by nuclear systems is the acre-year, which is defined as the use of one acre for one year. In the GESMO Report³⁶ the land-use value for light-water reactors (no recycling) for the years 1975 through 2000 is reported to be 2.8×10^7 acre-years. Recycling affects this figure by less than 20%,³⁶ and it will be shown that this 20% variation is of small importance to the discussion.

During the same 25-year period, cumulative electrical energy generated from nuclear reactors is estimated to be 35×10^{12} kWh(e).³⁷

In comparing the land use value for solar systems, it will be assumed that each system would generate 30×10^{12} kWh(e) over the same 25-year time span.

Solar Thermal (Central Receiver)

It is estimated that a 100 MW(e) power plant with sufficient storage capacity to operate up to 6 hours in the evening (in addition to daytime operation) would occupy an area of 2.4 square miles or 1.5×10^3 acres.³⁸ The design-point solar flux for this system would be available 2000 hours out of the year.³⁹ The 2000 hours of sunshine per year represents an average of 5.5 hrs/day. The storage facility for this plant is designed to deliver 6 hours of electricity at 70% load in the evening for every 6 hours of design point sunshine. Since this sunshine is available approximately 6 hrs/day on the average, and the plant is operating at full power during this period, it will be optimistically assumed that the plant will deliver 2 hours of electricity for each hour of sunshine. The assumption is optimistic because it assumes a perfect match between the insolation and the 6 hour storage capabilities. On days when the design point flux is available for a period longer than 6 hours the plant will still deliver only 6 hours of electricity in the evening. Furthermore, it is assumed that the electricity generated from storage is at full load, rather than 70% load.

The deliverable electrical energy (per acre) in one year for a plant of this type is calculated to be

$$100 \text{ MW(e)} \times \frac{2 \text{ hrs delivery}}{1 \text{ hr sunshine}} \times 2000 \frac{\text{hrs sunshine}}{\text{yr}} \times 10^3 \frac{\text{kW}}{\text{MW}} \\ \times \frac{1}{1.5 \times 10^3 \text{ acres}} = 2.7 \times 10^5 \frac{\text{kWh(e)}}{\text{acre yr}} .$$

The land-use for plants of this type, if they were available to generate the total cumulative electrical energy to be supplied by nuclear power plants to the year 2000, is then

$$\frac{35 \times 10^{12} \text{ kWh(e)}}{2.7 \times 10^5 \text{ kWh(e)/acre year}} = 13 \times 10^7 \text{ acre years.}$$

Photovoltaic

In an attempt to characterize a generic photovoltaic electrical-power producing plant located in the southwest, the following assumptions were made:⁴⁰

Net systems efficiency	8%
Total insolation	2300 kWh(e)/m ² -yr
Fraction of land covered by collectors	35%

The product of these factors gives a power density (power/land area) of 64 kWh(e)/m²-yr or 2.6×10^5 kWh(e)/acre-yr.

In supplying the electrical energy expected from nuclear power for the next 25 years the land use factor is calculated as

$$35 \times 10^{12} \text{ kWh(e)} / 2.6 \times 10^5 \frac{\text{kWh(e)}}{\text{acre-yr}} = 13 \times 10^7 \text{ acre years.}$$

Windmills

The rotor diameter of a windmill designed to generate a power of 1.5 MW(e) for wind speeds of about 25 mph is assumed to be 180 ft.⁴¹ The plant factor⁴¹ is taken to be 0.43. If a field of these mills were set up such that each windmill was at least six rotor diameters (D) apart, which is sufficient to prevent the turbulence from one windmill to affect another, and the smallest reproducible geometric sub-unit of the field is taken to be a triangle with sides of length D, then the electrical energy per unit area of such mills is given by

$$\frac{1500 \text{ kW(e)} \times .43 \times 8.76 \times 10^3 \frac{\text{hrs}}{\text{yr}} \times 5.28^2 \times 10^6 \frac{\text{ft}^2}{\text{mile}^2}}{(6 \times 180)^2 \text{ ft}^2 \times \cos 30^\circ \times 640 \text{ acres/mile}^2} \\ = 2.4 \times 10^5 \frac{\text{kWh(e)}}{\text{acre yr}} .$$

This is based on the fact that the density per unit area of objects placed on the corners of the triangles in a large field of adjoining

isosocles triangles is given by the sum of the fractional contributions of each object at each corner of the triangler ($3 \times \frac{60}{360}$), divided by the area of the triangle ($\frac{1}{2} D^2 \cos 30^\circ$). The land-use of these systems if they were to replace the power expected from nuclear reactors over the next 25 years is

$$35 \times 10^{12} \text{ kWh(e)} / 2.4 \times 10^5 \frac{\text{kWh(e)}}{\text{acre year}} = 15 \times 10^7 \text{ acre years.}$$

These results are summarized in Table IV.

Table IV. Comparative solar system land-use in supplying the cumulative net power expected from nuclear power plants [35×10^{12} kWh(e)] from 1975-2000^a

Plant type	Power per unit area [kWh(e)/acre-year]	Land-use (acre year)
Light water reactors		2.8×10^{1b}
Solar thermal Central receiver	2.7×10^5	13×10^7
Photovoltaic	2.6×10^5	13×10^7
Windmills	2.4×10^5	15×10^7

^aReferences to these data are given in the text.

^bLand use without Pu recycle. With Pu recycle it is approximately 20% less (Ref. 36).

The data indicate that under the conditions assumed for this comparison that nuclear energy is expected to be considerably more efficient in land-use than the solar systems that were studied, and therefore the consideration of the land used by solar vs that used by nuclear systems has little relevance in the discussion of solar energy as an alternate source of energy in GESMO.

RELATED SUBJECTS ON SOLAR ENERGY

Technical Problems

The technical problems associated with each of the solar systems are described below.

Heating and cooling

Sensitivity to dirt on the cover plates, susceptibility of these plates to breakage, unknown lifetime for the system, durability of selective coatings under high temperature operation, lack of an efficient method for cooling.

Process heat

Unknown lifetimes, inadequate storage for high temperature systems, corrosiveness of saline water when such is utilized (as in solar ponds).

Solar thermal conversion to electricity

Unknown boiler lifetimes, unknown reflector lifetimes, reliability of large numbers of tracking systems, thermal stresses and thermal cycling, maintenance of high vacuums under high temperature (distributed collector system), solidification of high temperature fluids, effects of weather and dust on heliostats.

Photovoltaic

Low efficiencies (approximately 10% at present), unknown lifetime, weather and dust effects, reliability at operating temperatures.

Wind energy

Cyclic stress effects, response of large systems to changing wind directions (horizontal shaft machines), response to sudden wind speed changes.

Ocean thermal

Efficiencies at low ΔT , reliability of massive heat exchangers, effects of the corrosive environment, stress-strain effects of ocean currents on enormous cold water intake pipe, parasitic power pumping losses, biofouling, underwater maintenance, transmission of electricity over long distance underwater.

Environmental Problems

In general, the environmental problems for most of the systems are thought to be small. The systems for which few environmental problems are envisioned are heating and cooling of buildings, process heat and the limited use of photovoltaics. An example of the latter is the use of photovoltaics as a supplemental source of electricity for homes.

Even when large land areas are covered in the production of central station electricity, either for solar thermal systems or for photovoltaic cells, the environmental problems are thought to be minimal. The location of these systems in desert regions might result in some reduction in the population of animal species which are dependent on the climate peculiar to the desert. On the other hand, flora and fauna that exist marginally in those regions, because of the intense heat, may flourish in the vicinity of the power plants. The aesthetics of these large systems leave much to be desired, but it is unlikely that their implementation will be inhibited for this reason only.

Windmills capable of producing large quantities of electricity [approximately 1000 MW(e)] are not under serious consideration. Therefore, many small systems must be employed for the electrical production of significant magnitudes. The effects on the weather of these systems

is uncertain, but serious problems in this regard are not anticipated. The noise that present systems produce will raise objections in large fields of windmills, and noise abatement for windmills is under investigation. Aesthetics are a potential problem but are unlikely to be serious.

The employment of many ocean thermal systems will disturb the downstream temperature gradients of the ocean. The magnitude of the problem is uncertain at the present time.

Social and Institutional Problems

There are few social problems anticipated; however, there are serious institutional problems that must be resolved before large scale solar energy utilization can take place. Among the most important of these problems are:

1. the legal rights of exposure to the sun, so that others may not obstruct the sun from reaching the collectors,
2. high capital costs which result in problems of financing,
3. use of large land areas and competing land use,
4. "wind rights" such as in 1,
5. industrial and safety codes,
6. zoning restrictions,
7. establishment of standards,
8. international law regarding ocean thermal plants, and
9. the security of these plants from sabotage.

CONCLUSION

It is concluded that the role of solar energy should have little effect on the considerations pertaining to GESMO.

APPENDIX

The problem is to calculate the probability for a combination of solar-electric and wind systems of having some fraction of the total power available at any time. If this probability is very high, then the electrical power industry could displace a corresponding amount of capacity with this specified fraction, since the industry could assume that this fraction is essentially always available. A systems - reliability quoted by industry is that corresponding to a 1 day failure-to-meet-demand out of 10 years, or a probability of success in meeting demand of 99.96%.²⁷

A first-estimate method of calculating the desired quantity is as follows: assume a widely dispersed (over the entire U.S.) solar-electric system with a total capacity of 100 MW(e) and with overnight storage capabilities such that a full day of sunshine will store sufficient energy to generate full capacity throughout the night. The demand on the system is assumed to be constant for simplicity. Along with the 100 MW(e) solar, assume a wind-electric system similarly dispersed with a total capacity of 20 MW(e) and no storage. Out of a total capacity of 120 MW(e), an arbitrary amount, say 10 MW(e), will be selected, and the probability that at least this 10 MW(e) will be available at any time from the entire system will be calculated.

Let $p_s(x)dx$ = probability that the power available at any time from the solar system lies at a value within dx about x

$p_w(y)dy$ = a similar definition for the wind system,

with

$$p_s(0) \neq 0, p_w(0) \neq 0$$

and

$$p_s(x > 100) = p_w(y > 20) = 0$$

along with

$$\int_0^{100} p_s(x) dx = \int_0^{20} p_w(y) dy = 1$$

Since data for these distribution functions are not yet available, some not unreasonable assumptions will be made, namely that for the solar system the probability that at least 10 MW(e) is available at any time is assumed to be equal to the fraction of the days out of the year that clouds will cover 90% or less of the entire U.S. This number is estimated to be 340/365, or 0.93, i.e.

$$\int_{10}^{100} p_s(x) dx = 0.93, \text{ and hence } \int_0^{10} p_s(x) dx = 0.07$$

Wind systems are presently designed to operate at wind speeds of approximately 15 M/hr or greater, and it will be arbitrarily assumed that at any time at least half the power is available from the wind system with a probability of 50%, i.e.

$$\int_{10}^{20} p_w(y) dy = 0.50, \text{ with } \int_0^{10} p_w(y) dy = 0.50$$

Assuming complete independence between the solar and wind systems and also complete independence among the various constituents of the solar system and of the wind systems, the probability that at least 10 MW(e) will be available at any time from the entire system, $P(\geq 10)$, is then

$$\begin{aligned} P(\geq 10) = & \int_{10}^{100} p_s(x) dx \int_0^{10} p_w(y) dy + \int_0^{10} p_s(x) dx \int_{10}^{20} p_w(y) dy \\ & + \int_{10}^{100} p_s(x) dx \int_{10}^{20} p_w(y) dy \end{aligned}$$

$$+ 1/2 \left[\int_0^{10} p_s(x) dx \int_{10-x}^{10} p_w(y) dy + \int_0^{10} p_w(y) dy \int_{10-y}^{10} p_s(x) dx \right]$$

The term in brackets represents the contribution to the probability from the cases where the power available from either system is below 10 MW(e), but the sum of the power from each system equals or exceeds 10 MW(e). To save tedious rewriting, this contribution will be termed G. Substituting the assumed values for the integrals into the expression,

$$P(>10) = 0.965 + G.$$

One can get an overestimate of G by the following considerations: the p's for the wind and solar will very likely have the form

i.e., the probability that power will be available at any time will be relatively small for zero power and also for maximum power, and it will be greatest somewhere in between the two extremes. If one then assumes that each of the distributions are uniform, i.e., if one assumes that $p_s(x)dx = dx/100$, and $p_w(y)dy = dy/20$, which represent straight horizontal lines with values $p_s(x) = 1/100$ and $p_w(y) = 1/20$, these values at the low end of the scale should be greater than the true values. Utilizing the uniform values

$$G = 1/2 \left[\int_0^{10} \frac{dx}{100} \int_{10-x}^{10} \frac{dy}{20} + \int_0^{10} \frac{dy}{20} \int_{10-y}^{10} \frac{dx}{100} \right] = 0.25 \quad .$$

When added to the expression for $P(>10)$, the sum gives an estimate of the desired overall probability as

$$P(>10) = 0.990$$

with in fact

$$.965 < P(>10) < 0.990 \quad .$$

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