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SERI/TP-733-617 CONF-800352--4
UC CATEGORIES: UC-59,62

SOLAR PONDS & THEIR APPLICATIONS

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MARCH 1980

PRESENTED AT THE
7TH ENERGY TECHNOLOGY
CONFERENCE
WASHINGTON, D.C., MARCH 25, 1980

PREPARED UNDER TASK NO. 3525.12

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1536 Cole Boulevard
Golden, Colorado 80401

A Division of Midwest Research Institute

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

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Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $3.00
Printed Copy $4.00

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1.0 ABSTRACT

Solar ponds are probably the simplest and least expensive technology for conversion of solar energy to thermal energy. The solar pond is unique in its ability to act both as collector and as storage. The cost of a solar pond per unit area is considerably less than that of any active collector available today. The combination of their economic and technical factors make solar ponds attractive for district heating and industrial process heat applications. Solar ponds have the potential to displace significant quantities of fossil fuel in low-temperature heating applications in nonurban areas.

2.0 INTRODUCTION

The solar pond is probably the simplest technique for direct thermal conversion of solar energy. It is simultaneously a collector of solar radiation and a large body of thermal storage. Any pond converts insolation to heat, but most natural ponds quickly lose that heat through vertical convection within the pond, and through evaporation and convection at the surface. The solar pond artificially prevents either vertical convection, or surface evaporation and convection, or both. Because of its massive thermal storage and of measures taken to retard heat loss, the typical pond takes weeks for a 10°C temperature loss, even in the absence of insolation. Thus, the solar pond converts an intermittent energy source (solar radiation) into a reliable source of thermal energy.

Solar ponds can be operated at virtually all habitable latitudes. In some locations their surfaces may freeze in winter, but storage temperatures will remain high enough for low-temperature applications, and some insolation will still penetrate the ice. Solar ponds are less expensive per unit collector area and per unit of thermal output than flat-plate collectors, and they are more efficient at high temperatures. Their chief disadvantage compared with flat-plate collectors is that (with the possible exception of the shallow solar pond) they cannot be mounted on rooftops, therefore, the area requirement for solar ponds is a concern. They would have little or no applicability in urban areas. Nevertheless, as Section 5.1 will show, they have the potential to displace a very significant amount of present-day fossil fuel usage.

3.0 ADVANTAGES OF SOLAR PONDS

Solar ponds eliminate or minimize certain problems usually associated with solar technologies—principally high cost and variability of output. The following are the chief advantages of solar ponds.

3.1 A Working Technology

It has been established numerous times, extensively in Israel, but also in Ohio, New Mexico, and Canada, that the salt gradient solar pond is a working technology (Sargent, 1979; Zangrando, 1978; Saulnier, 1975).

3.2 Low Cost

Typical solar pond capital costs are \$10 to \$40 per square meter—almost an order of magnitude lower than flat-plate collector costs. System conversion efficiencies to thermal energy range from 10% to 30%. Assuming a moderately favorable site and application (200 W/m^2 average insolation, 20% efficiency, \$30/m^2, 20% fixed charge rate), the energy cost is 1.7¢/kWh_{th} or \$5.02/MBtu. Assuming a superior site and application (250 W/m^2 average insolation, 25% efficiency, \$20/m^2, 15% fixed charge rate), the energy cost is 0.5¢/kWh_{th} or \$1.61/MBtu.

3.3 Massive Storage

The quantity of thermal storage in a solar pond is measured, not in hours or days, but in multiples of weeks. A typical solar pond contains 20 weeks of thermal storage. Thus, solar ponds can provide heat in winter resulting from insolation captured in summer and fall. Even if heat collection is insignificant in winter, the solar pond will provide the desired output.

3.4 Collection Efficiency at High Temperatures

Solar ponds are more efficient solar collectors than flat-plate collectors at high operating temperatures.

3.5 No Backup Requirement

Due to its massive storage and its high operating temperature, the solar pond requires no backup for space heating and hot water and low temperature industrial process heat applications. This is a very significant advantage over most other renewable energy technologies.

3.6 Favorable Energy Payback

Solar pond construction is neither materials intensive nor energy intensive. Earth serves as the support structure and water as the collection, storage, and heat transfer medium. Recovery of the collected energy requires little investment of energy.

3.7 Simplicity

Solar ponds are simple to build and maintain.

3.8 Decentralized

Due to their lack of requirement for backup and their relatively low-technology production and maintenance requirements, solar ponds are a truly decentralized technology. They are especially appropriate for remote locations, communities seeking energy self-sufficiency, and developing countries.

3.9 Potential for Significant Fossil Fuel Displacement

Solar ponds have the potential to displace from one to six quads of fossil fuel in the near and intermediate future in rural and suburban areas. Solar ponds are assumed to have less applicability in urban areas (i.e., central cities), due to area requirements and the infeasibility of mounting solar ponds on rooftops (with the possible exception of shallow solar ponds).

4.0 DESCRIPTION OF SOLAR PONDS

4.1 Salt Gradient Pond

The salt gradient pond (Fig. 1) is the most highly developed type of solar pond (Tabor, 1963, 1965; Nielsen, 1979). Research on it has been under way in Israel since the early 1960s. Recently, Israel has activated a 150 kW solar pond electric plant on the Dead Sea (Sargent, 1979). Israel plans an eventual 2000 MW of electricity to be generated with solar ponds. The cost is estimated at $2,000/kW.

The salt gradient pond contains a stratified salt solution. The surface water contains little or no salt. Salt concentration then increases with depth, reaching a high concentration near the bottom. The effect of this salt concentration gradient is that the weight of the solution increases with depth. Hence, thermal buoyancy convection is suppressed. Thermal buoyancy convection (i.e., warm water rising) is normally the principal mode of heat transfer in a body of water exposed to sunlight. With this convection suppressed, the salt-gradient solar pond retains much of the heat absorbed from incident insolation.

Principal costs for the salt-gradient pond are for earth moving, salt, and bottom liner to prevent leakage. In favorable sites, any of these costs may possibly become negligible.

4.2 Deep Saltless Pond

The deep saltless pond retards heat loss, not by suppressing thermal buoyancy convection, but by retarding losses from the surface of the pond. This is accomplished through surface glazings and additional night insulation (Taylor, 1977). Various means of providing the additional night insulation have been proposed. Work on deep saltless ponds is in its infancy. The deep saltless pond may, however, offer an attractive alternative to the salt gradient pond where salt costs are high, or the possibility of environmental damage due to salt runoff is a serious concern (Edesess, August 1979).

4.3 Shallow Solar Pond

The shallow solar pond proposed and developed at Lawrence Livermore Laboratories (Dickinson, 1976; Casamajor, 1979) is not unlike a low-cost flat-plate collector. Water in large shallow plastic bags is heated by incident insolation and pumped to an underground tank for nighttime storage. A major advantage of the shallow solar pond is that it may be located on rooftops, if the building structure is adequate to support the weight. A disadvantage of the shallow solar pond is that it requires much plumbing and pumping equipment and separate nighttime thermal storage, and is thus less inexpensive than deep solar ponds.

Salt-Gradient Solar Pond

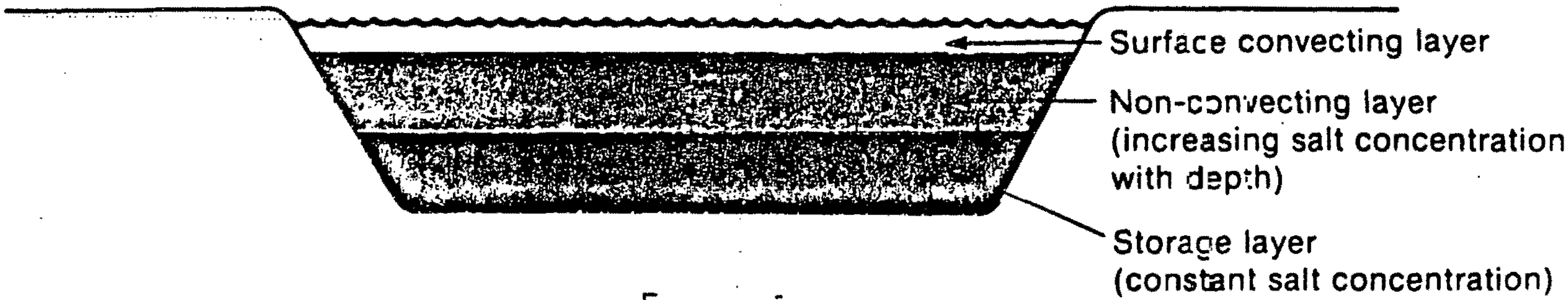

FIGURE 1

4.4 Innovative Nonconvecting Solar Ponds

It has been proposed that thermal buoyancy convection may be suppressed through the use of gels or viscosity stabilizers, or membranes placed at strategic planes within the pond.

4.5 Collector/Pond Storage Combinations

In some designs, a massive body of water is used as thermal storage, but not as a collector (i.e., it is not exposed to insolation). In a Swedish project, for example, (Margen, 1978) permanent surface insulation floats on a pond, while flat-plate collectors rest on the insulation. The flat-plate collectors heat water and drain to the pond for storage. Such applications demonstrate the usefulness of solar ponds for their value as storage alone.

5.0 SOLAR POND APPLICATIONS

Solar ponds are readily applicable to such low-temperature uses as residential or commercial heating and hot water, low-temperature industrial or agricultural process heat, or preheating for higher temperature industrial process heat (IPH) application. Combined with organic Rankine cycle engines or thermoelectric devices, solar ponds may be used for electric power generation. By using the heat to run an absorption chiller, solar ponds may be used for cooling.

5.1 Solar Pond Potential

The potential of solar ponds for displacing fossil fuels in the United States is great. To estimate potential market size, the approximate number of quads (10^{15}Btu) of energy used in each potential solar pond application was compiled in Table 1. It was assumed that no market for solar ponds is possible within urban areas, but that nonmetropolitan areas (i.e., rural) have prime potential, and metropolitan areas outside cities (i.e., suburban) also have potential for solar pond penetration. Energy end use was assumed to be divided in proportion to the population among nonmetropolitan areas, metropolitan areas outside cities, and cities.

Table 2 shows the potential of solar ponds in nonmetropolitan areas alone at 15%, 30%, and 100% penetration rates. At 15% penetration, solar ponds would provide 1-1/4 quads, and at 30% penetration, they would provide 2-1/2 quads. Table 3 shows the potential of solar ponds in both nonmetropolitan areas and metropolitan areas outside cities. At 15% penetration, the potential is over 3 quads, and at 30% penetration it is more than 6 quads.

5.2 District Heating Applications

To minimize heat losses at the pond edges, it is best to maximize the ratio of pond area to pond perimeter. Therefore, a small pond will not be as efficient as a larger one. Thus, it is better for residential heating applications to build one large pond for a group of houses than to build a small pond for each house.

Table 4 shows the results of sizing a salt-gradient solar pond using the simple technique described in Edesess (December 1979), at various locations in the United States. The load is assumed to be 50 kW_{th} on the average, attaining a maximum of 70 kW_{th} during the peak demand period. Sizing calculations were performed for winter peaking and summer peaking loads. Summer peaking loads are more likely at lower latitudes where solar ponds may be used for cooling. The surface area requirement is unaffected by the timing of the peak demand. The depth requirement is affected, however; greater depth is required for a winter peaking load. Sizing was performed both for a "hot pond" (75°C average/50°C minimum) and a "warm pond" (60°C average/40°C minimum) at each location.

The surface area requirement for the hot pond to serve the specified load ranges from about 1/2 acre in Miami, Fla., and Los Angeles, Calif., to a little over 2 acres in Boston, Mass. Surface

Table 1. **QUAD POTENTIAL OF SOLAR PONDS IN THE U.S. (80 Quad Total U.S. Energy Consumption Assumed)**

		Market Size				
		Region				
		Northeast	North Central	South	West	Total
Space Heating	Residential: Non-Metropolitan	.52	1.39	.82	.44	3.17
	Residential: Metropolitan, Outside City	1.53	1.75	.84	.78	4.90
	Commercial: Non-Metropolitan	.24	.64	.38	.20	1.46
	Commercial: Metropolitan, Outside City	.71	.81	.39	.36	2.27
Water Heating	Residential: Non-Metropolitan	.09	.20	.28	.09	.66
	Residential: Metropolitan, Outside City	.27	.26	.28	.20	1.01
	Commercial: Non-Metropolitan	.02	.05	.07	.02	.16
	Commercial: Metropolitan, Outside City	.07	.07	.07	.05	.26
Cooling	Residential: Non-Metropolitan	0.00	.08	.20	.06	.34
	Residential: Metropolitan, Outside City	0.00	.12	.20	.14	.46
	Commercial: Non-Metropolitan	0.00	.06	.16	.06	.28
	Commercial: Metropolitan, Outside City	.02	.09	.17	.14	.42
Industrial Process Heat	Low-Grade Heat	.16	.19	.12	.07	.54
	Pre-Heat	1.07	1.28	.84	.48	3.67
Agriculture	Low-Grade Heat	0.00	.10	.10	.10	.30
Electricity	Irrigation	0.00	.10	.10	.10	.30
Clothes Drying	Residential: Non-Metropolitan	.01	.03	.03	.01	.08
	Residential: Metropolitan, Outside City	.03	.03	.04	.02	.12

Table 2. QUAD POTENTIAL OF SOLAR PONDS BY APPLICATION (Non-Metropolitan Areas Only)

	Percentage of Penetration		
	15%	30%	100%
1. Residential	0.64	1.28	4.25
2. Commercial	0.28	0.57	1.90
3. Industrial	0.23	0.47	1.57
4. Agricultural	0.09	0.18	0.60
TOTAL	1.25	2.50	8.32

Table 3. QUAD POTENTIAL OF SOLAR PONDS BY APPLICATION (Non-Metropolitan & Metropolitan Areas Outside Cities)

	Percentage of Penetration		
	15%	30%	100%
1. Residential	1.61	3.22	10.74
2. Commercial	0.73	1.46	4.85
3. Industrial	0.63	1.26	4.21
4. Agricultural	0.09	0.18	0.60
TOTAL	3.06	6.12	20.40

Table 4. REQUIRED SOLAR POND SURFACE AREAS AND DEPTHS AT VARIOUS LOCATIONS IN THE UNITED STATES

						Pond Sizes for 50 kW_{th} Avg./70 kW_{th} Max. Load[a]			
						Winter Peaking		Summer Peaking	
Region	Location	Latitude (°)	Insolation (W/m^2) Avg./Min.	Ambient Temp. (°C) Avg./Min.	Pond Temp. (°C) Avg./Min.	Area (acres)	Depth (m)	Area (acres)	Depth (m)
Pacific	Los Angeles	34	209/112	16.5/12.5	75/50	0.52	3.5	0.52	2.6
	Los Angeles	34	209/112	16.5/12.5	60/40	0.38	4.2	0.38	2.7
Mountain	Denver	39	206/96	10.1/-1.2	75/50	0.63	3.7	0.63	3.0
	Denver	39	206/96	10.1/-1.2	60/40	0.44	4.5	0.44	3.3
West N. Central	Omaha	41	174/67	9.7/-6.6	75/50	1.04	3.6	1.04	3.2
	Omaha	41	174/67	9.7/-6.6	60/40	0.64	4.3	0.64	3.4
West S. Central	Dallas	33	193/103	19.0/7.4	75/50	0.59	3.4	0.59	2.6
	Dallas	33	193/103	19.0/7.4	60/40	0.42	4.2	0.42	2.8
East N. Central	Chicago	41	160/53	10.3/-4.3	75/50	1.37	3.5	1.37	3.1
	Chicago	41	160/53	10.3/-4.3	60/40	0.76	4.2	0.76	3.4
East S. Central	Jackson, MS	32	185/93	18.3/8.4	75/50	0.66	3.4	0.66	2.7
	Jackson, MS	32	185/93	18.3/8.4	60/40	0.45	4.1	0.45	3.3
New England	Boston	42	145/53	10.7/-1.6	75/50	2.07	3.2	2.07	2.9
	Boston	42	145/53	10.7/-1.6	60/40	0.96	3.8	0.96	3.2
Middle Atlantic	Philadelphia	40	154/62	12.6/0.2	75/50	1.42	3.2	1.42	2.9
	Philadelphia	40	154/62	12.6/0.2	60/40	0.77	3.9	0.77	3.1
South Atlantic	Miami	25	194/134	24.2/19.6	75/50	0.50	2.9	0.50	1.9
	Miami	25	194/134	24.2/19.6	60/40	0.37	3.6	0.37	1.9

[a]Approximately the demand of 25 to 50 households.

area requirements for the warm pond range from a little over 1/3 acre in Miami and Los Angeles to almost 1 acre in Boston. The depth requirement ranges from 1.9 m for a summer peaking load in Miami for both hot and warm ponds to 4.5 m for a winter peaking load and a warm pond in Denver. (Note that the depth requirement may be relaxed by increasing the surface area and, thereby, raising the entire temperature profile of the pond.)

The pond sized in each case, with allowance for different climates and consequent user loads, would be sufficient to serve roughly 25 to 50 households.

5.3 Industrial Process Heat Applications

To assess the feasibility of solar pond technology for IPH applications and compare the suitability of ponds with more conventional solar technology, two industrial applications were selected for analysis (Brown, 1979).

One application focuses upon the hot water (60° C) requirements for aluminum can washing in a Colorado manufacturing plant where cans are shaped and trimmed from sheet stock, then washed and dried before being sent for bottom coating and painting. The total annual energy requirement for can washing on one process line is 2.5 X 10^{12} joules (2,185 MBtu). Energy is currently supplied by natural gas at $1.93/GJ.

The second application is for hot water (82° C) used in washing in a large Colorado commercial laundry. Total annual energy to be supplied is 4.3 X 10^{12} joules (4,085 MBtu). Energy is currently supplied via natural gas at $1.85/GJ.

Solar pond systems were sized to assist the IPH needs of the metal can manufacturer and the commercial laundry. In theory, a pond could have been sized to provide 82° C continuous output, as required for the commercial laundry. The incremental surface area and depth required, however, to increase the pond's minimum output temperature from 80° C to 82° C is considerably greater than that required to increase it from 60° C to 62° C. Therefore, there is likely to be an optimal size at which the marginal cost of increasing the pond's area is equal to the cost of backup energy. Hence, the optimal solar pond may use backup, even though it may be feasible to size a solar pond large enough to require no backup.

For the metal can washing application, a solar pond was sized to achieve an annual average temperature of 55° C, with an annual high of 65° C, and an annual low of 45° C. It was assumed that a 5° C loss would be suffered in exchanging heat from the pond. Hence, at its peak temperature of 65° C, the pond will just satisfy without backup the application's requirement for 60° C water. At all other times, it will require backup to boost the temperature. The pond is 5143 m^2 (1.27 acres) in surface area and 4.9 m deep. The capital cost of the pond alone is $128,000 if salt is free, $173,000 if salt costs $10/ton, and $218,000 if salt costs $20/ton. The costs of the heat exchanger and piping were conservatively assumed to be $8/$m^2$ of the pond surface area.

For the laundry application, a solar pond was sized to achieve an annual average temperature of 65° C, with an annual high of 80° C, and an annual low of 50° C. This pond is 3552 m^2 (0.88 acre) in surface area and 3.2 m deep. Its capital cost is $76,000 with free salt, $94,000 at a salt cost of $10/ton, and $112,000 at a salt cost of $20/ton. Again, heat exchanger and piping costs were assumed to be $8/$m^2$.

A rate of return calculation was performed for each application using the method identified in Dickinson (1979). Equity financing was assumed with a 20-year service life, 7-year depreciation, 50% tax rate, and 20% investment tax credit. No salvage value was taken. Two levelized fuel prices are assumed in each case: (1) current quoted price of fuel with an 8% rate of escalation, and (2) fuel price of $5/GJ ($5.27/MBtu) escalating at 10% per annum. An efficiency of conversion to delivered heat of 85% in metal can washing and 75% in the laundry is assumed.

Installation of any sort of solar IPH system in either application does not offer adequate return on investment when compared to current costs of natural gas and a fuel price escalation rate of

8%. However, when compared to natural gas at \$5/GJ escalating at 10%, the solar pond systems usually provide a rate of return in excess of 15%, which is generally sufficient to warrant commitment of funds in general service investments. Hence, solar ponds justify serious consideration as economic alternatives for low-temperature IPH. In addition, it appears that the return from solar pond systems is not highly sensitive to salt cost.

5.4 Electric Power Generation

In combination with organic Rankine cycle engines or thermoelectric devices, solar ponds may be used for the generation of electric power. Conversion efficiency is low—on the order of 1% to 2% from insolation to electric output—but costs are so low that solar pond electric applications may be economical in many cases. Much work is being done in Israel on solar pond-organic Rankine cycle engine generation of electricity (Sargent, 1979). Thermoelectric devices can also be coupled with solar ponds to convert low-grade heat to electricity and may provide a viable means of generating electricity in certain applications, particularly in the Third World (Jayadev, 1979). It should be noted that solar-pond electric generation has a significant advantage over other solar-electric systems in that, because of the inherent solar pond storage, electricity is available on demand, rather than only intermittently.

6.0 CONCLUSION

Solar ponds have considerable potential for economically providing district heating for residential and commercial areas, industrial process heat, and electric power. There has as yet, unfortunately, been little research, development, and demonstration of solar ponds in the United States, although there has been a major effort undertaken in Israel. Work is needed to research inexpensive salts for salt gradient ponds and surface glazings and night insulation for saltless ponds. An accumulation of experience with demonstration ponds and commercial ponds in the United States would provide needed lessons in design and maintenance techniques. With a little effort applied to their development, solar ponds are one of the most promising near-term solar technologies.

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☆U.S. GOVERNMENT PRINTING OFFICE:1980 — 677-175/88