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SOLAR PONDS FOR DISTRICT HEATING AND ELECTRICITY GENERATION

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SOLAR PONDS FOR DISTRICT HEATING AND ELECTRICITY GENERATION

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Abstract

This paper considers system requirements, performance, and costs for the application of solar ponds to district heating and to electricity generation. It focuses on the optimal sizing and configuration of the solar ponds themselves, but other system features are also investigated and discussed. Performance and costs range widely, depending upon location and component costs, particularly upon salt costs for the salt gradient pond. Distribution cost for district heating is also an important parameter that can vary widely. Both salt gradient and saltless ponds are considered.

Introduction

The solar pond has been receiving intensified attention recently as an inexpensive technology for conversion of solar energy. In addition to its low cost, the solar pond offers the advantage of massive inherent thermal storage, thus eliminating the problems of intermittent solar radiation.

Most thoroughly developed is the technology of the salt gradient solar pond.[1] In the salt gradient pond (Fig. 1), salt is dissolved in high concentrations in the lower depths or "storage layer." At the top of the pond, the "surface layer" is virtually free of salt. Between these two layers is the "nonconvecting layer," in which salt concentration increases with depth. Because of the steadily increasing salt concentration, and therefore weight, of the solution in this layer with depth, the normal tendency of the warmed water to rise to the surface is suppressed. Thus, the insolation absorbed as heat in the depths of the pond is preserved.

Other solar pond technologies have been proposed[2] in which vertical convection within the pond is not prevented, but heat loss at the surface is suppressed instead. These designs employ either transparent glazings alone (Fig. 2), or opaque insulation over the top of the pond combined with glazings within which water is pumped to absorb the insolation.

These solar pond designs develop a very large quantity of stored low temperature heat, which is almost immune to daily fluctuations in climate and which maintains its temperature through cold winters. Applications of solar ponds that have been proposed and studied include: residential and commercial space and water heating on a community scale--i.e., district heating; low-temperature industrial process heat; electricity generation; and cooling using absorption chillers. Examining two of these applications: district heating and electricity generation, this paper discusses the various aspects of system design that must be considered and optimized in tailoring the solar pond to these applications. It focuses particularly on the questions of pond size, configuration and optimal temperature, but deals with the other elements of the systems as well.

District Heating

Salt gradient solar ponds are being examined in this study for possible application to neighborhood-scale district heating. Ponds have a number of inherent characteristics that would be advantageous in providing the energy to meet this type of load. First, solar ponds have large time constants with high thermal capacities and are thus relatively insensitive to daily variations in the weather. Second, there are economies of scale for larger ponds because the significance of the edge loss effects decreases as the surface area increases. And finally, in contrast to many other solar technologies, ponds may be economically sized to provide nearly 100% of the energy requirements of the load.

This study represents a preliminary investigation of the technical and economic feasibility of incorporating solar ponds into new subdivisions to

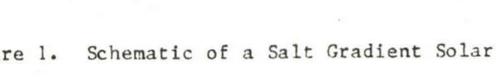

Figure 1. Schematic of a Salt Gradient Solar Pond

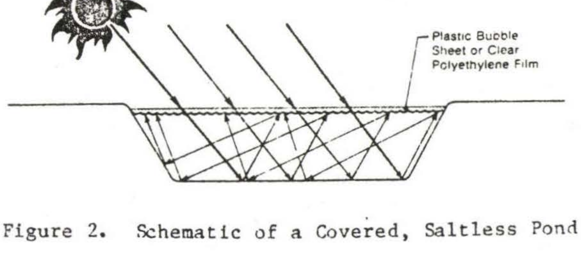

Figure 2. Schematic of a Covered, Saltless Pond

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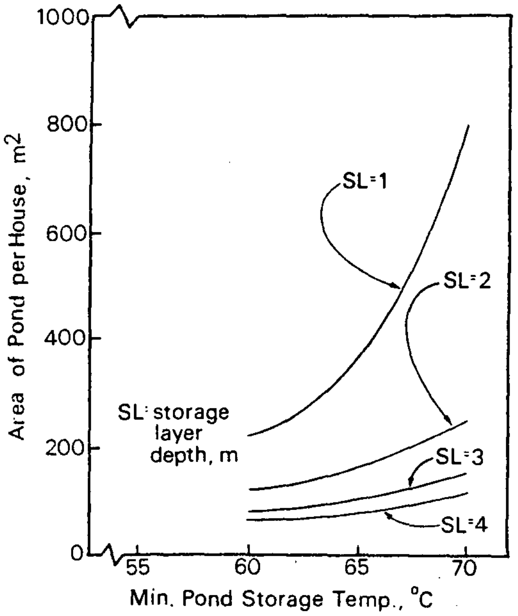

Figure 3a. Pond Area Required per House as a Function of Minimum Pond Temperature and Storage Layer Depth for a 50-House Community in Washington, D.C.

provide district heating and domestic hot water. A description of the neighborhoods modeled is presented along with the load estimation procedure. Results of pond sizing to meet district heating needs in Fort Worth, Texas and in Washington, D.C. are shown next. Finally, capital and labor cost estimates for both the ponds and the distribution systems are discussed.

Description of Districts Modeled

To limit the scope of the study, only new neighborhoods were considered, specifically those typical of suburban subdivisions. Two locations were examined--Fort Worth, Texas, a fairly mild climate with high average insolation, and Washington, D.C., which has colder winters and fewer sunny days. A typical single-family residence for each location was selected for analysis, and each is defined by a set of building characteristics that predominate for new construction in that locale, as detailed in Ref. 3. Each house meets or exceeds ASHRAE standard 90-75.[4]

Neighborhood sizes of 50, 200, and 500 homes were examined in this study. Each neighborhood was assumed to be composed entirely of single family homes, with a density of four units per acre, or 1076 units/km^2.

Load Calculation

Daily heating loads for one year were computed using a TRNSYS transient simulation.[5] Meteorological inputs were obtained from the TMY data set for Fort Worth and Washington, D.C.[6] A TRNSYS-compatible load model with inputs and parameters that characterize the construction of each house was used to determine the heating loads. Domestic hot water usage was estimated for the single-family dwellings and corresponding loads calculated and added to the house heating loads. Losses in transmission, distribution, and heat exchange were assumed to be 5%, and therefore each daily heating load value was increased by 5%. Load files for each district heating scenario were then computed by multiplying each year's home heating and hot water load by the number of houses in the district.

Pond Sizing

Load files generated as described in the preceding section were used as inputs to SOLPOND, a computer code that models the thermal performance of salt gradient solar ponds.[7] The 50-house neighborhood was first modeled. Several ponds were sized to meet the thermal load in each location. Parameters varied include minimum storage layer temperature and storage layer depth. The nonconvecting zone in all cases was 1-m thick, the surface convecting zone was 0.5-m thick, and the salt used was sodium chloride. Figures 3a and 3b show the effect on required pond area of raising the minimum storage layer temperature to meet the same thermal load in each city. Storage layer depths of 1 m, 2 m, 3 m, and 4 m at Fort Worth and depths of 2 m, 3 m, and 4 m at Washington, D.C. were examined. The minimum temperature selected will affect the flow rate requirements and heat exchanger characteristics, both at the pond and at each house. A deeper pond provides more thermal capacitance and thus allows a higher minimum storage temperature to be maintained for the same surface area. Minimum temperatures ranging upward from 60°C were investigated in these simulations, on the assumption that ponds would be sized to serve 100% of the load without backup. This may not, in fact, be the most economical practice. A slightly smaller pond with fuel-fired backup or booster systems or with heat pump assistance is likely to prove more economical in many cases.

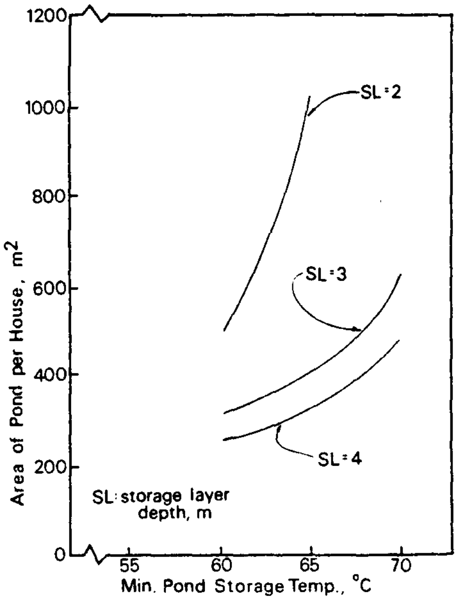

Figure 3b. Pond Area Required per House as a Function of Mimimum Pond Temperature and Storage Layer Depth for a 50-House Community in Fort Worth, Texas

To examine the effect of neighborhood size on the required pond area per house, ponds were sized to meet the load of 50, 200, and 500 houses in Washington, D.C. Although edge losses become less significant as the pond diameter increases, it is evident from Fig. 4 that scaling up from a 50-house neighborhood to a 500-house neighborhood causes only a 15% to 20% reduction in the pond surface area required per unit (for the same storage layer depth and minimum temperature).

Cost Assumptions

Cost estimates for the district heating systems are divided into two categories: 1) solar pond materials and labor costs and 2) distribution system costs. Associated pond costs of the salt and liner were determined by telephone contact with several manufacturers and distributors in May 1980. Excavation costs were estimated from the Means Handbook.[8] Table 1 contains a summary of the salt, liner, and excavation costs used in this analysis. The salt costs can vary widely from the quoted prices and it may be possible to realize lower costs.

Table 1. POND COST SUMMARY

Excavation	\$ 1.40/m^3
Liner	\$ 5.40/m^2
Salt (F.O.B.)	\$52.80/1000 kg
Shipping	
Fort Worth	\$11.44/1000 kg
Washington	\$30.36/1000 kg

Distribution costs are too uncertain at this point to support a detailed cost analysis. Costs for transmission and distribution piping have been estimated in a study conducted by Lesse et al.,[9] where district heating piping costs for urban (specifically Boston) retrofits were cited. The type of pipe chosen was a direct-buried, mechanical-joint, ductile iron pipe that is insulated, coated, and wrapped with a waterproofing jacket. In a rural project, where there are no existing streets to be torn up, the costs would be substantially less. Furthermore, for solar pond district heating applications in which temperatures are well below 100°C, very low cost plastic piping may be used. Continuing work at SERI will investigate these possibilities, as well as the optimization of piping size and configuration taking into account piping and pumping costs and required flow rates.

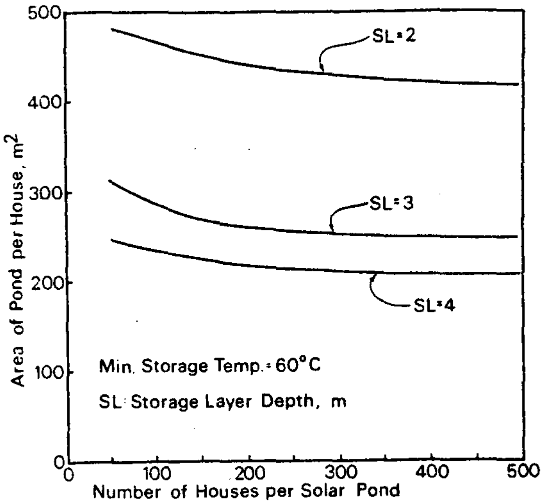

Figure 4. Required Pond Area as a Function of Neighborhood Size in Washington, D.C.

Pond Capital Costs

Using the cost estimates in Table 1, the pond capital costs were computed for the cases being examined. Figures 5a and 5b show these costs for various storage depths and for minimum storage temperatures of 60°C and 65°C, for both Fort Worth and

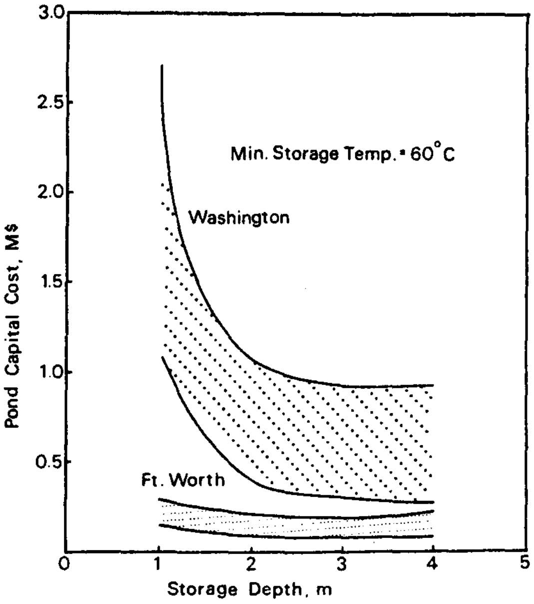

Figure 5a. Pond Capital Cost as a Function of Storage Layer Depth for a 50-House Community and a Minimum Pond Temperature of 60°C. (Upper Curves Correspond to Salt at Quoted Market Values; Lower Curves Assume Salt at \$11/1000 kg.)

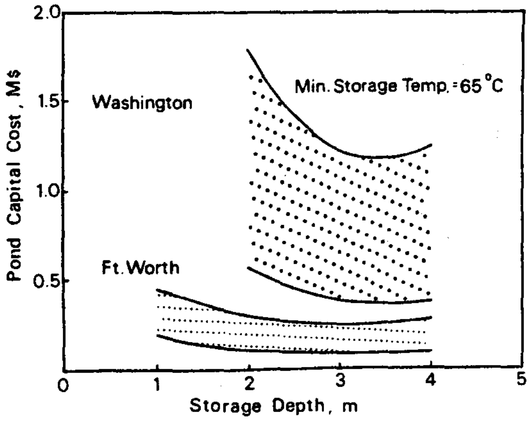

Figure 5b. Pond Capital Cost as a Function of Storage Layer Depth for a 50-House Community and a Minimum Pond Temperature of 65° C. (Upper Curves Correspond to Salt at Quoted Values; Lower Curves Assume Salt at \$11/100 kg.)

Washington, D.C. The shaded areas represent the range of pond capital cost as a function of salt cost. At the top of the shaded portion, delivered salt costs of $83.16/1000 kg at Washington, D.C. and $64.24/1000 kg at Fort Worth were used in the analysis. These costs are consistent with the bulk prices (F.O.B. plus rail shipping) quoted by suppliers in telephone conversations. The curve at the bottom of the shaded area was generated assuming the availability of free salt, with $11/1000 kg as a nominal freight charge. Possible sources of free salt include concentrated brine from desalination plants, and salt by-products from power and chemical plant effluent.[1] An important result of Fig. 5 is an apparent optimum pond depth for a given minimum pond storage temperature. For example, in Fort Worth, at a 60°C minimum temperature, the cost of the pond (with high salt cost) reaches a low of $204,200 for a storage depth of about 3-m (diameter = 72 m). Even though at a 4-m storage depth the required diameter is only 68 m, this deeper pond costs 11% more to meet the same thermal load. The 68-m pond actually has a greater volume and requires more salt than the 72 m version, accounting for the cost differential.

Discussion

The results show that salt gradient solar ponds may be sized for district heating without backup at capital costs ranging from less than $2,000 per house to over $20,000 per house, depending upon location, minimum pond temperature, and salt cost. If fossil or biomass backup or heat pumps are used, the minimum pond temperature--and therefore the pond cost--will be lower. At current conventional energy prices, it will usually be most economical to employ backup or heat pumps with solar pond district heating systems. Ongoing research will determine the proper combination of the pond with backup or heat pumps as a function of the various materials and energy costs. Another systems question that must be addressed is whether centralized or individual-house backup or heat pumps are more economical. As the costs of conventional energy rise, it will eventually become economical to use solar ponds without backup and even to use solar pond electric generation to provide the mechanical energy for pumping.

As mentioned earlier, distribution systems and costs require much further study. Solar pond district heating systems involve a lower source temperature than do fossil fuel-fired systems, or most waste heat and geothermal systems. The chief advantage of this low temperature is that less expensive materials may be used. The disadvantage is that backup may be required in some instances. Further study should be directed toward optimization of materials and system configurations in solar pond district heat systems.

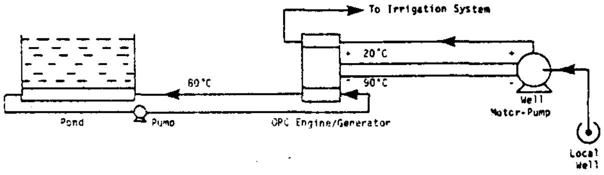

Figure 6. Schematic of ORC Engine-Generation Using a Pond for the High Temperature and Pumped Irrigation Water for the Cold Temperature

Electricity Generation

Although most pond applications examined in the United States are for low grade heat, ponds also have potential for electricity generation.

Electricity can be generated from the low temperature heat provided by ponds using organic Rankine-cycle engines, which use working fluids such as freon, propane, or toluene. These engines generally operate with an efficiency that is about 40% of Carnot efficiency, the thermodynamic limit of performance. A schematic of this type of generation system is shown in Fig. 6. Another possible conversion cycle involves the use of thermoelectric generators. These devices, although less efficient than organic Rankine-cycle engines, are potentially less expensive, particularly at low operating temperatures.

Optimization of Pond Temperature

The goal of system design for electricity generation is to maximize the electricity produced from a given amount of insolation; i.e., for a given collector area. Higher efficiencies reduce unit energy costs.

An idealized efficiency calculation was made for solar pond electricity generation. The overall efficiency of solar pond electric conversion is the product of the efficiency of collection η_{pond} and the efficiency of conversion to electricity η_{gen}. For the pond's collection efficiency,

$$\eta_{pond} = (\tau\alpha) - \frac{T-T_A}{I} U \quad . \tag{1}$$

The $\tau\alpha$ product is the percentage of insolation that reaches the pond's storage layer, and the second term describes the thermal losses. The pond temperature is T, T_A the ambient temperature, I the insolation, and U the thermal loss coefficient. This expression can be simplified to

$$\eta_{pond} = \eta_o \left[1 - C(T - T_A)\right] \quad , \tag{2}$$

where η_o is the $\tau\alpha$ product and C is a constant. Note also that $(1/C) = T_S - T_A$, where T_S is the pond's stagnation temperature, equal to $T_A + \tau\alpha I/U$.

The efficiency of the conversion system can be described as a percentage of the maximum theoretically possible:

$$\eta_{gen} = K \frac{T - T_A}{T} \quad , \tag{3}$$

where K is the percent of Carnot efficiency.

The overall conversion efficiency η_c is the product of these two efficiencies, or

$$\eta_c = \eta_o \left[1 - C(T - T_A)\right] K \frac{T - T_A}{T} \quad . \tag{4}$$

By taking the derivative of η_c with respect to T, the value of T that yields the highest η_c can be found. The highest system efficiency occurs when the pond temperature is the geometric average of the stagnation temperature and the ambient temperature; i.e.,

$$T_{opt} = \sqrt{T_S T_A} \quad . \tag{5}$$

Salt Gradient Ponds and Saltless Ponds

In addition to salt gradient ponds, consideration was also given to saltless ponds with glazings on the surface. Although there would be vertical convection within these ponds, multiple glazings spaced 19.05 mm apart could provide some insulation. Advantages of glazings would be an increased collection efficiency and reduced evaporative losses. The cost of salt would be avoided, as well as the danger of environmental damage because of salt water leaks. There could be any number of glazings, with increasing insulation attendant upon the increase in number of air gaps. As the number of glazings increases, optical efficiency is lowered, but the thermal resistance and the stagnation temperature are increased.

Figure 7 shows the difference in efficiency characteristics for salt gradient ponds and saltless ponds with different numbers of insulating air gaps. All four configurations of saltless ponds absorb about twice as much energy as salty ponds, but the insulating value of the air gaps does not approach that of the nonconvecting zone in the salt pond. The stagnation temperatures for saltless ponds are therefore much lower than for salt ponds.

Increasing the number of insulating gaps to increase stagnation temperature would be possible, but impractical. The cost of the plastic glazing material would be quite high--$3/m^2 for Teflon. A more appropriate way to limit losses would be to place opaque insulation, such as foamed polystyrene, on the surface of the pond, and put the appropriate number of glazings over that. The upper surface of the insulation would be used as an absorber plate, and water would be pumped over the plate, below the glazings, and back into the pond. Thermal losses would be reduced significantly.

Solar Pond Electric Generation Costs

The performance of the generating system was modeled with both salt gradient and glazed, insulated saltless ponds. The transmittance of the pond covers was determined assuming a Tedlar cover with Teflon for the inner glazings, mounted horizontally at 40° latitude. The conductance of the air gaps was 8.5 W/m^2°C (R value 0.75) and that of the surface insulation 0.57 W/m^2°C (R value 10).

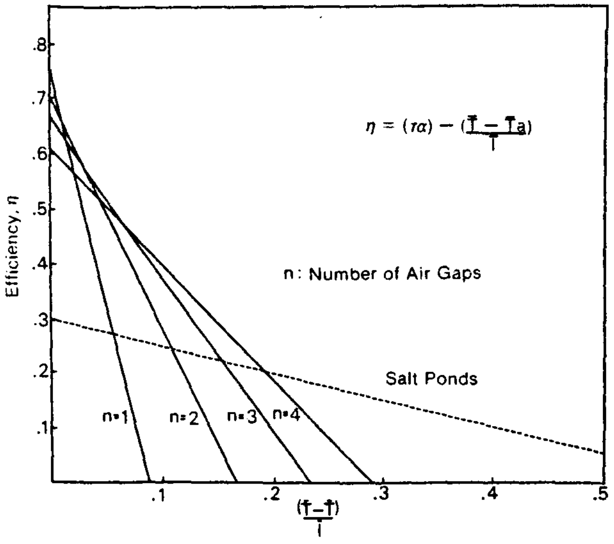

Figure 7. Efficiency Characteristics for Various Pond Configurations

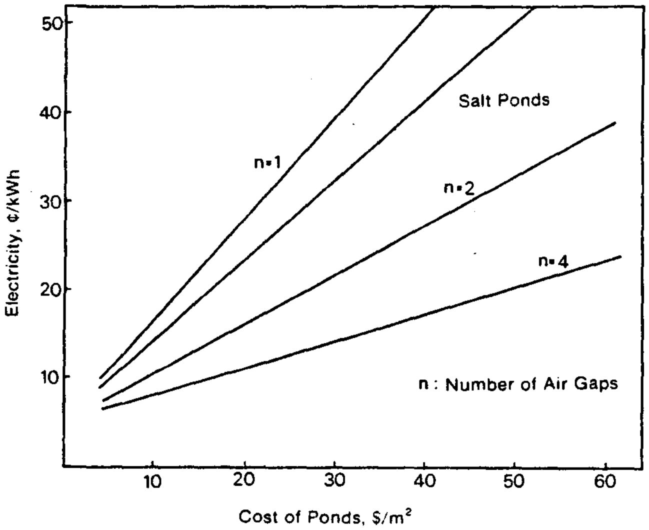

Figure 8. Cost of Electricity Versus Pond Costs for Various Configurations of Ponds

The life of the pond was assumed to be 20 years. The organic Rankine-cycle engines were assumed to have a life of four years, with regular intensive maintenance, and a cost of $1000 per kilowatt of capacity.

For this system the capital cost can be simply calculated from:

$$\text{cost} = \frac{C_{pond} \times C_F}{\bar{I} \times \eta_c} + C_{gen} \quad , \tag{6}$$

where C_{pond} is the cost of the pond per square metre, C_F is the capacity factor ($C_F = 0.8$ assumed), $\bar{I}$ is the average insolation, and C_{gen} is the cost per kilowatt of engine capacity. The cost per kilowatt hour was calculated using an 18% annual fixed charge rate for the pond, and a 34% annual fixed charge rate for the engine owing to its shorter expected life. Figure 8 shows the cost of electricity for varying pond costs. Three types of insulated, glazed saltless ponds are represented together with the salt gradient pond. The insulated and glazed pond provides lower cost electricity than the salt pond if its capital cost is equal to or less than that of the salt pond. This may be the case in locales where only high cost salt is available. The electricity costs, though high, are generally competitive with other solar electric generation systems, and in uniquely favorable circumstances in which pond costs are very low--such as where free salt is available--the cost of solar pond electricity is competitive with conventional systems.

Conclusions

Preliminary cost figures for solar pond district heating systems and for solar pond electric systems are attractive enough to warrant further investigation. There is much work to be done in detailed design of solar pond district heating systems. The relative sizes of the various components of these systems--ponds, backup, heat pumps, piping and pumping systems--should be determined through economic optimization considering all of the component costs and their manner of integration. Pond size and geometry may be optimized within a given context. The relative size of pond and backup, however, may be quite sensitive both to fuel costs and pond costs, and particularly to the local cost of salt. Saltless ponds show great potential, especially for electricity generation where salt costs are high. For district heating with solar ponds, improved low cost and low-temperature distribution system technologies must be developed.

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