NREL/TP-471-5099 • UC Category: 231 • DE93010004

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Prepared for the 1993 ASME/ASES Joint Solar Energy Conference, Washington, D.C., April 26-30, 1993.

NREL

National Renewable Energy Laboratory
(formerly the Solar Energy Research Institute)
1617 Cole Boulevard
Golden, Colorado 80401-3393
Operated by the Midwest Research Institute
for the U.S. Department of Energy
under Contract No. DE-AC02-83CH10093

December 1992

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A03

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR)*; and publication NTIS-PR-360 available from NTIS at the above address.

ECONOMIC STATUS AND PROSPECTS OF SOLAR THERMAL INDUSTRIAL HEAT

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SUMMARY

This paper provides estimates of the levelized energy cost (LEC) of a mid-temperature parabolic trough system for three different development scenarios. A current technology case is developed that is representative of recent designs and costs for commercial systems, and is developed using data from a recent system installed in Tehachapi, California. The second scenario looks at design enhancements to the current technology case as a way to increase annual energy output and decrease costs. The third scenario uses the annual energy output of the enhanced design, but allows for cost reductions that would be possible in higher volume production than currently exist.

A simulation model was used to estimate the annual energy output from the system, and the results were combined with cost data in an economic analysis model. The study indicates that R&D improvements in the current trough system show promise of reducing the (LEC) by about 40%. At higher production rates, the LEC of the solar system with R&D improvements could potentially be reduced by over 50%.

INTRODUCTION

Solar thermal technologies are capable of providing heat across a wide range of temperatures, making them potentially attractive for meeting end use energy requirements in industrial process heat applications, commercial heating, and commercial cooling. Flat plate concentrators can use either air or water as a working fluid, which is typically supplied to an end use at temperatures from 40-80°C. Parabolic trough technology can supply heat at delivery temperatures of 100-350°C, and parabolic dish technologies can provide heat at temperatures to 800°C. Solar furnaces can provide heat at even higher temperatures, and with their high flux capabilities offer innovative approaches to materials processing and other applications.

Solar thermal technologies for industrial applications span the gamut from proven technologies that are in early phases of commercial development to conceptual ideas still in the developmental stages. A good characterization of the industrial market for solar thermal technologies might be significant promise, but little current utilization. A recent study estimated that the potential market for solar industrial process heat from parabolic trough systems could be as high as 5.5 quads in the industrial and commercial sectors by the year 2030 if a vigorous R&D program is pursued (Demeter, 1991). Current utilization of solar heat systems in the industrial and commercial sectors is several orders of magnitude below this potential.

The intent of this study is to examine some of the issues related to moving solar thermal heat technology from the current level of industrial implementation to the large potential indicated by the previous study. Gaining insights into these issues requires a specific technology focus, since potential performance and cost improvements are technology specific. In this study, solar troughs were selected as the specific technology to investigate.

STUDY APPROACH

The initial activity in the study was to select a baseline system to characterize the performance and cost that could be expected from a current technology solar trough system. The annual performance of the system was estimated at three different sites (Denver, Phoenix, and Bakersfield) using the TRNSYS computer code. These sites were selected somewhat arbitrarily to provide insights into results at an excellent site (Phoenix), a site with a good direct normal solar resource (Denver), and an intermediate point (Bakersfield). It should be noted that none of these sites is representative of an "average" location for the US, but represent reasonable early market locations for solar heat installations. This data was used to calculate a levelized energy cost (LEC) for the current solar system using a methodology described elsewhere (Brown et al. 1987). The LEC is a life-cycle cost calculation that produces an energy cost that is constant over the project's lifetime.

The LEC exactly covers all costs of the solar project, including return on investment. LEC's reported in this study are calculated in constant dollars, meaning that they are fixed in 1991 price levels and factor out the effects of inflation over the plant's lifetime. It is important to note that for the purposes of evaluating the attractiveness of a solar heat technology, the LEC cannot be compared to current fuel costs, but must be compared to a similarly calculated LEC for the fossil fuel alternative. In this study we have calculated a baseline LEC for several natural gas scenarios to provide a comparison basis. In the natural gas calculations it was assumed that the solarplant would operate in a fuel-saver mode, hence the natural gas LEC does not include the capital cost of the natural gas system. Economic assumptions used in the LEC calculations are shown in Table 1.

Following the economic evaluation of the current technology, a number of technology improvements were considered which could increase the annual energy output of the trough plant. These improvement options were generated though discussions with the solar industry, and generally would require varying amounts of R&D to achieve. These design improvements were evaluated for a case with current costs for the solar hardware, and a case for lower costs which would be appropriate for higher volume production.

CURRENT TECHNOLOGY PERFORMANCE AND COST DATA

The system we selected to represent the current state-of-the-art for trough heat is based on the recent trough installation at the California Correctional Institution in Tehachapi, California. The Tehachapi system was selected for modeling in this study for several reasons. First, it is the most recent large-scale parabolic trough system that has been installed in the United States, and one of the only major industrial process heat trough systems installed in this country

Table 1. Economic Assumptions for LEC Calculations

Variable	Value	Reference
Inflation rate	5%	General Assumption
System Life	30 yrs	Planned operating lifetime
After tax discount rate	10.4%	Representative of cogeneration ROI requirements (Hansen, McOuat & Associates, Inc. with Scully Capital Services, Inc. 1989)
Depreciable Life	5 yrs	Current tax law
Investment Tax Credit	10%	Current tax law
Combined Tax Rate	40%	Generation Assumption
Other Taxes	1%	General Assumption

Table 2. Annual Energy Estimates for Current Trough Heat Systems

Location	Phoenix, AZ	Bakersfield, CA	Denver, CO
Annual Energy Output, GJ	7720	7281	6170

within the last several years. The company that constructed the system, Industrial Solar Technology (IST), recommended the Tehachapi system as their best representation of a trough installation using current technology.

The Tehachapi system is designed to operate with an outlet temperature from the solar field of just under 150°C. The system transfers its thermal energy to the load through two serially connected heat exchangers to deliver energy to two thermal loads at temperatures of 105°C and 55°C.

Based on the design performance of the Tehachapi system, simulations were conducted using the TRNSYS code to estimate the annual energy delivered by a current technology solar plant at three different locations. The sites were selected somewhat arbitrarily to span a range of insolation and climatic data where solar heat systems might be economic in the near-term. The results of this analysis is summarized in Table 2 (Hale and Williams 1992).

The capital costs for the current solar technology case was based on the Tehachapi plant, which had a total installed cost of $633,600. On a per-unit basis, this corresponds to an initial cost of $\$237/m^2$ of collector area.

The Tehachapi system has not yet provided representative maintenance data since the system was undergoing shakedown operations during much of 1991. For this reason, the annual maintenance costs have been estimated based on experience for a similar system operating at the Adams County Detention Facility (ACDF) in Brighton, Colorado. Although the ACDF system is much smaller than the Tehachapi plant (725 m^2 versus 2676 m^2) the experience at the ACDF facility can be scaled to provide a reasonable estimate of for the maintenance costs of Tehachapi. Annual costs for normal maintenance scaled up from the ACDF facility are indicated in Table 3. A loaded rate of $20 per hour was used for all labor estimates. Note that the system is designed around the concept of requiring little scheduled maintenance in order to minimize the life-cycle costs.

A separate category of maintenance costs is the periodic capital replacements expected to occur sporadically throughout the plant lifetime. For this system the only costs that could be expected with certainty are for replacement of the reflective film. Reflective film lifetime is currently an item of considerable uncertainty. Outdoor testing on solar films has only been performed for a limited number of years, so that it is still necessary to extrapolate accelerated test data to predict lifetimes of most available materials. In addition, the outdoor testing that has been done has indicated that lifetime is very site specific, and can vary significantly between locations such as Phoenix and Denver.

The lifetime for the SA85 reflective material was estimated by NREL optical materials researchers as about 8 years, based on outdoor test data and results from NREL simulated tests. As noted above, there is a considerable uncertainty in this estimate. The costs for the film replacement were estimated by IST to be approximately $\$21/m^2$; this is considerably higher than the initial cost of the film since it accounts for replacement of the back sheet to which the film is laminated for adhesive, and for field labor for replacement.

It is not known whether replacement film costs will be treated as routine maintenance expenditures (and expensed in the year they occur) or will be treated as capital investments, which will have to be depreciated. For the purposes of this study, we elected to use the more conservative approach and assumed that all film replacement would be treated as a capital investment, with a 5 year depreciable life. Treating the film replacements as a maintenance cost would result in slightly lower energy costs because of the more favorable tax treatment.

ENHANCED TECHNOLOGY PERFORMANCE AND COST DATA

The future technology plant was assumed to have the same heat delivery temperatures and capacities as the current technology plant, but the plant performance and annual energy output were increased by incorporating a number of specific design

Table 3. Projected Maintenance Costs—Current Trough System

	Parts	Labor
System Washing	$490	$1360
Routine Maintenance Inspections	$115	$1840
Parts Replacement/Repair	$1149	$1380
	$1754	$1380
TOTAL MAINTENANCE COSTS = $6,334/yr ($2.4/m^2)		

enhancements. A list of the improvement options evaluated is shown in Table 4. The potential improvements in the annual energy production were evaluated using the TRNSYS computer model; the identification and analysis of these options is described in a companion paper (Hale and Williams 1992). The projected annual energy at each location for the future technology cases is shown in Table 5.

In addition to enhancing the annual energy output, the design changes investigated will also impact the costs associated with building and operating the solar heat plant. In some cases these cost impacts are fairly easy to quantify, but in others there is a great deal of uncertainty. A summary of the projected cost variations for each of the options, along with a discussion of the relative uncertainty in the estimates, is discussed below. Much of the information on the cost projections was provided by IST.

Evacuated receivers are without question more expensive than the receiver design used in the baseline design. Additional equipment and production steps include addition of bellows and a getter for the vacuum, and labor to evacuate the receiver. It is also possible that additional care would be required in transportation and handling of the receivers that could increase the cost relative to the baseline receiver. IST has not performed a detailed evaluation of evacuated receiver costs, but provided a preliminary estimate of approximately $50 incremental costs for a 10 foot evacuated receiver tube. For the IST trough design, this translates to an incremental cost of $7/m^2.

IST is in the process of completing a project on application of antireflective coatings, and completed a cost estimate for the process as part of the project. IST provided an estimate of $35 per 10 foot receiver tube for the application of the antireflective coating, including materials, labor, and capital costs. For the IST trough design, this translates to an incremental cost of $5/m^2. Because these costs have recently been estimated in a fair amount of detail, they are believed to have a fairly low level of uncertainty.

Cermet surfaces have been used by LUZ, but currently are not commercially available. Based on past discussions with ex-LUZ personnel, it is believed that the production of cermet coatings on receiver tubes at the production level that LUZ operated is less expensive than black chrome coating used in the baseline design. Cermet surfaces also have the advantage of having much longer life with more stable properties. The barrier to producing cermet surfaces is the equipment required: LUZ reportedly invested approximately $10 million in the early 1980s for the equipment they used to produce their receivers. For the purposes of this study, we evaluated the cermet option assuming that it would be applied at fairly large production volumes and would add no additional cost to the receiver. It appears unlikely that the cermet surface will be economic until production volume for trough systems increases substantially.

For the improved reflector case, the costs and life characteristics of the reflector are based on NREL goals for advanced optical materials that are shown in Table 6. Although there is obviously still considerable uncertainty about obtaining an optical material with these properties, a recent NREL solicitation identified three contractors with innovative approaches which show promise to meet the goals. Table 6 compares these goals to 2 currently available reflective materials and one experimental material. Lifetime estimates shown in Table 6 are highly site specific and also fairly uncertain. The experimental

Table 4. Design Enhancements Evaluated

Name	Design Variation	Performance Benefit
Evacuated	Replace current receiver with evacuated receiver.	Reduced convective heat losses from receiver tube
AR Coating	Add antireflective coating to the glass receiver cover tube.	Increase the cover glass transmittance from 0.91 to 0.96
Cermet	Replace black chrome receiver coating with cermet surface.	Improve absorber properties from absorptance=0.95 and emittance=0.25 to absorptance=0.96 and emittance=0.10
Cleaning	Use reflective film with abrasion resistant properties and low surface energy	Improve average reflectivity from 82% of new value to 94% of new value
Improved Reflective Film	Replace SA85 reflective film with film having performance of ECP-305 but with improved cost and lifetime.	Increase the new reflectivity from 0.83 to 0.92 and set the average reflectivity to 94% of new value

Table 5. Annual Energy Estimates for Enhanced Trough Heat Systems

Location	Phoenix, AZ	Bakersfield, CA	Denver, CO
Annual Energy Output, GJ	12178	11557	10148
Percentage Increase over Current Technology	58%	59%	65%

Table 6. Characteristics of Various Optical Materials

Material	Cost,$/m^2	Reflectivity	Life,Years	Replacement Cost, $/m^2
Aluminized Polymer (3M SA-85)	$10	85%	≈ 8	$21
Silvered Polymer (3M ECP-305)	$30	92%	≈ 5	$41
Silvered Polymer (NREL Experimental)	$30	92%	≈ 8	$41
Advanced Polymer (Goal Based)	$10	92%	10	$15

silvered polymer shown in the table represents a recent NREL development that is similar to ECP-305 but has several enhancements to provide longer life. The NREL experimental film has been holding up well under accelerated tests. It is believed that the modifications are sufficiently minor so the experimental film will not cost significantly more than ECP-305 at similar production levels.

Based on the cost modifications discussed above, the enhanced technology case was estimated to cost approximately $\$250/m^2$, compared to the current technology cost of $\$237/m^2$. Annual O&M costs for the two cases are assumed to be about the same, with recurring costs for reflector replacement as shown for the advanced polymer case in Table 6.

PRODUCTION LEVEL IMPACTS ON PLANT COSTS

In addition to the design changes discussed in the last section, the cost of energy from trough heat systems can be expected to drop if the annual production level of solar components increases. Currently trough heat systems are produced in very limited numbers, and in this environment system costs are much higher than they would be in even modest production levels. There are a number of reasons that contribute to this phenomena, including:

- Materials costs will decrease when ordering in larger volumes.
- Utilization of equipment and facilities used in the manufacturing of solar collectors will increase, thereby reducing the cost of these items on a unit cost basis.
- Larger production volumes allow investments in more efficient manufacturing systems that are not economic at low production levels.
- Many types of project development, financing, and overhead costs increase in a less than linear manner with production volume, so their unit costs will decline substantially as production increases.
- To the extent that higher production level is achieved through larger scale projects, economies of scale in field installation will contribute to cost reduction.
- Learning during the process of manufacturing and installation of large numbers of solar components will contribute to more efficient production.

While there are many compelling reasons to believe that costs of solar troughs will decrease with higher production, quantifying the amount of reduction is difficult. While many of the effects can be readily estimated in conventional manufacturing cost estimates, such activities are generally time consuming and are difficult to do definitively without data that generally is available only to the manufacturer. In addition, some effects (such as learning) are subjective without a large body of component production data to estimate from.

As part of this study we contacted several prominent manufacturers of trough and flat plate solar systems to see if they could provide quantitative information on how costs could be expected to decline with production volume. In general, most manufacturers we spoke with agreed with the premise that higher production rates could greatly reduce unit costs, but indicated that they were generally unable to quantify this effect. One manufacturer estimated that a factor of 10 increase in production volume would about half his production costs.

Some prior estimates for a low-cost parabolic trough performed by IST developed concentrator cost estimates for several production volumes. [T. Wendelin, 1991] Results of this study are shown in Table 7 (note that the values in Table 7 are concentrator costs only and not total system costs).

For the Tehachapi plant, the concentrator cost was on the order of $\$150/m^2$. Using the information in Table 7 as a basis, approximately $\$80/m^2$ could be reduced from the system cost in higher production volumes based on concentrator cost reductions alone. This estimate is fairly consistent with the estimate from the other manufacturer than a factor of 10 increase in the current production level could cut costs about in half. Using the value of $\$80/m^2$ for the cost reduction provides an estimate of $\$170/m^2$ for the R&D enhanced case when produced in large volume.

LEVELIZED ENERGY COST RESULTS

Results of the LEC calculations for the 3 sites and 3 development scenarios are shown in Figure 1. For

Table 7. Production Volume Effects on Concentrator Cost for a Specific Trough Design

Annual Production Level, m^2	Unit Cost, $\$/m^2$
1,000	$188
10,000	$ 99
100,000	$ 70

the current technology cases, the projected LEC ranges from $7.4/GJ in Phoenix to $9.3/GJ in Denver. For comparison purposes, a LEC from a natural gas system was also developed. Natural gas is currently the fuel of choice where available because of its low cost, perceived future price stability, and clean burning characteristics. As such, it forms the toughest alternative competition for solar heat technologies. The scenario that was examined for natural gas was selected to represent a potential near-term target market for solar heat systems, and as such is at the high end of natural gas applications, but with characteristics that could be reasonably expected to be found in industry today. This scenario was developed for a boiler with an efficiency at the lower end of average systems, a gas price that is average for the US commercial sector, and EIA average price escalation rates. The values used in the analysis were a gas system annual efficiency of 67%, a gas cost today of $4.6/GJ, and a real price increase of 2.4% annually. The LEC calculated for the gas energy cost in this scenario is $9.5/GJ. This provides at least some indication that there are applications today where trough heat is competitive with natural gas.

The R&D enhanced systems show a dramatic decrease in the LEC, with the decrease being about 45% for each of the three sites. A comparison of how each of the individual R&D options affects the LEC for the Phoenix site is shown in Figure 2. Each of the R&D options shown is a cost effective enhancement of the current system. The most significant decrease in the LEC is accounted for by the improved reflective film, which in itself decreases the LEC of the current system by 24%. Note that the individual LEC decreases in Figure 2 are not additive because combinations of individual performance improvements are not additive.

The high production scenario incorporates both the R&D enhancements to the current design as well as cost reductions associated with larger production volumes. The LEC projections for the high production volume scenario vary between $3.4/GJ for Phoenix to $4.1/GJ for Denver. Compared to the current technology case, the LECs for the high production volumecase are about 55% lower.

CONCLUSIONS

The projected energy costs for the current trough systems evaluated were in a range that could be competitive today with at least some natural gas applications, and certainly with more expensive energy sources.

Continued R&D improvements to reduce the energy costs of trough heat systems appears warranted based on the results of this study. Several design changes were identified that would significantly enhance the economic attractiveness of trough heat systems. Even at the low production levels existing today, a system which combined the best of these improvements could reduce the energy cost of trough heat by about 40%. This improved system would be much more economically attractive relative to conventional energy sources.

The high production scenario projected extremely attractive energy costs for the trough heat system, which could be expected to be competitive in a wide range of applications against natural gas and other fossil fuels. If these projections can be achieved through continued development of the trough heat technology over the coming decade, then parabolic trough heat plants could become significant contributors to the national energy needs in the commercial and industrial sectors.

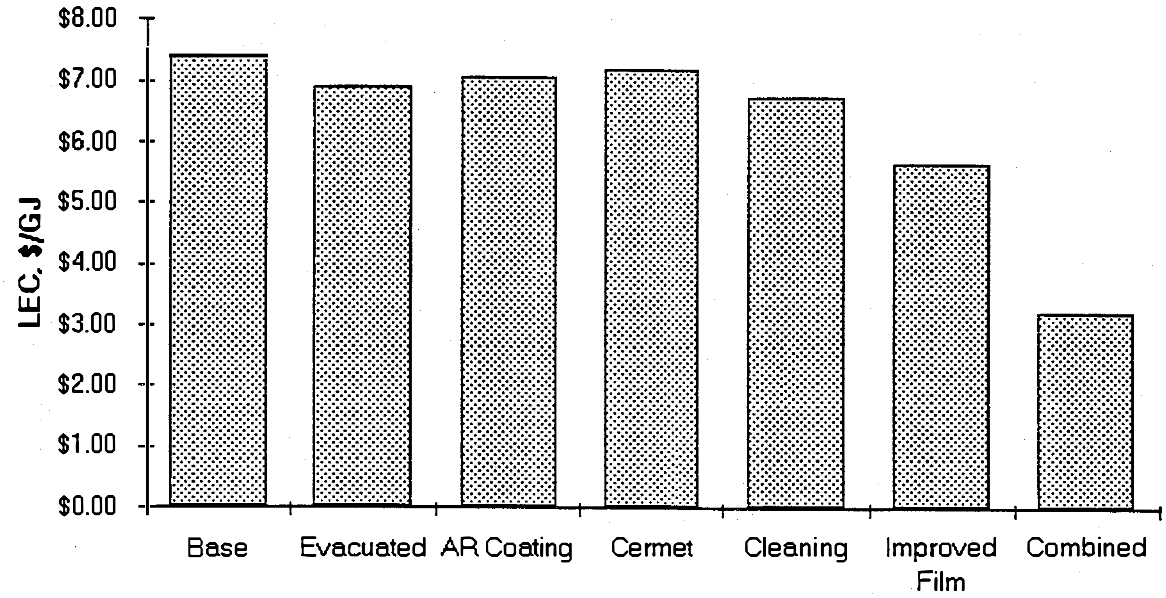

Figure 1 Comparison of Design Enhancements for Phoenix

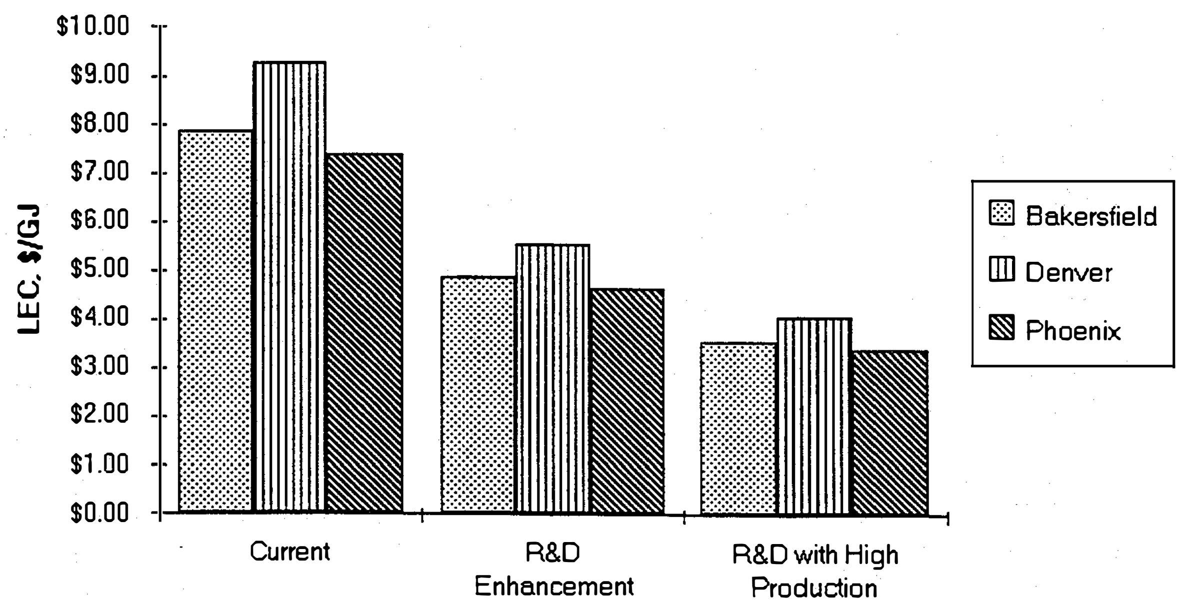

Figure 2 Trough Levelized Energy Cost Projections

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ACKNOWLEDGEMENTS

Funding for this study was provided by the U.S. Department of Energy. Industrial Solar Technology provided data on the Tehachapi system, along with many helpful suggestions during this study. This effort would not have been possible without their contributions.

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