# WREF 2012: ADVANCED PARABOLIC CONCENTRATOR FOR GRID COMPETITIVENESS

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ABSTRACT

A project to reduce the cost of solar power from a parabolic trough collector field to less than $0.09 per kWh in 2020, to render it competitive with fossil fuel derived power, is described. The cost-optimized design (SkyTrough®DSP) builds on knowledge gained in the development of the SkyTrough® parabolic trough concentrator. As with the SkyTrough, SkyTroughDSP is based on the use of a silvered polymer film, allowing for large monolithic reflectors, and high optical accuracy. The final result of the optimization is a larger parabolic trough, with higher concentration and operating temperature. This paper describes the optimization process used to arrive at the new design, and presents the detailed results.

## 1. INTRODUCTION

The goal of the research was to develop a parabolic trough collector that enables solar electricity generation for a 200-250 MWe baseload power plant with a Levelized Cost of Energy (LCOE) of 9¢/kWhe, a capacity factor of 75%, a limit of 15% fossil fuel fraction, a fossil fuel cost of $6.75/MMBtu, and $25.00/kWht thermal storage at a domestic installation corresponding to Daggett, CA. SkyFuel realized this goal by increasing trough aperture and operating temperature above the current state-of-the art for parabolic trough collector fields. The “SkyTrough for Dispatchable Solar Power” (SkyTrough DSP) will advance the state-of-the-art in parabolic troughs for utility applications, with a larger aperture, higher operating temperature, and lower cost.

We examined the design of almost every parabolic trough component from a perspective of load and performance at aperture areas from 500 to 2900m$^2$. The result of our optimization is a trough design of larger aperture and higher operating temperature than has been fielded in large, utility scale parabolic trough applications. The basic configuration is a Solar Collector Assembly (SCA) with 8m aperture width, 150m length, and an operating temperature of 500°C.

We conclude that meeting the project goal is practical, and intend to field the baseload parabolic trough collector (SkyTroughDSP) into 2014 markets.

## 2. BACKGROUND

The SkyTrough is a highly optimized parabolic trough, and forms the basis for development of the new trough. The SkyTrough is our current product, and we have complete understanding of its design, performance and cost. The optical efficiency (0.773) and thermal performance of the SkyTrough [1] match or exceed all troughs in the market. The SkyTrough represents an aggressive baseline design. The basic design selections made for the SkyTrough resulted in a state-of-the-art collector based on both cost and performance. Departures from that baseline for SkyTroughDSP (“DSP”) were made only where a path to significant cost reduction was identified.

The major cost components of the SkyTrough, shown in figure 1, are the receiver, mirror panel, space frame, and drive. Secondary components include parabolic ribs, torque plates, receiver supports, and support pylons.

Receivers represent a significant fraction of installed cost (20-30%), impact performance, and limit operating temperature. Conversations with lead suppliers of receivers and related components indicate that 500°C will be within the operational limits of product offerings in 2012 and beyond.

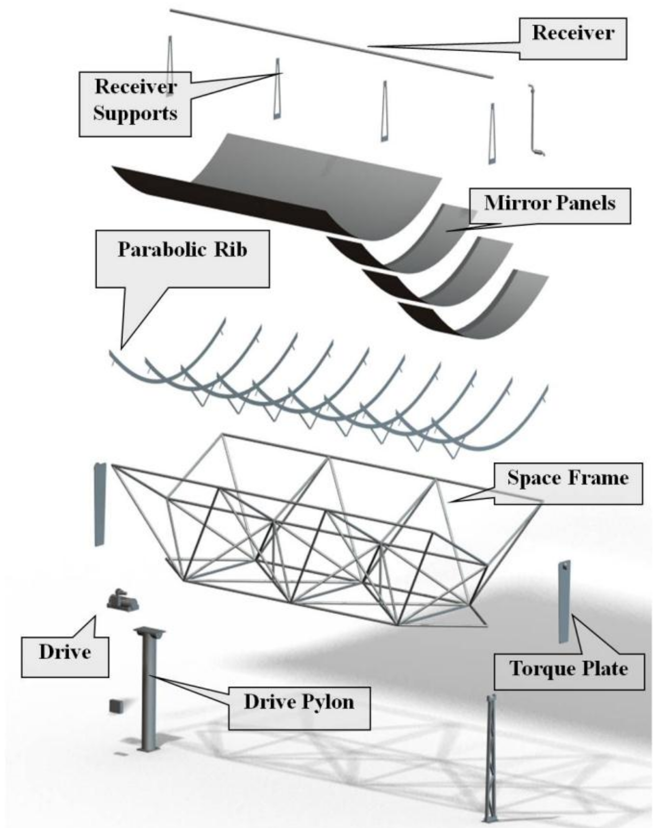


Fig. 1: Major components of SkyTrough module.

A major product differentiator in the SkyTrough is the use of a silvered polymer film as a reflector (ReflecTech®). SkyFuel was founded on the use of this advanced film because it reduces installed cost. Two significant improvements were made in the film to help achieve the cost reduction goal; outdoor lifetime was increased to 35 years, and solar-weighted hemispherical reflectance was increased by a full percentage point.

Functionally, the module structural support transfers the wind forces (the dominant environmental load in parabolic troughs) to the pylons and drives, while providing the foundation, or tracking platform, for the optical surface. The support must provide adequate stiffness to maintain optical accuracy under operating wind loads; however, the fundamental design is generally dictated by intermittent extreme loads (high wind speeds) that occur when the collectors are not operating.

For the space frame, we compared aluminum to steel, as a function of aperture, using standard space frame analysis. We assumed the geometry, executed a finite element analysis to define the elemental loads, optimized each element for lowest weight, and converted weight to cost. Frame width and depth increase in proportion to aperture width. We assumed the module and SCA length were identical to the SkyTrough. All struts and chords are cylinders of constant wall thickness. The finite element analysis is used to predict loads (see figure 2). The model includes parabolic ribs and mirror panels to allow a non-uniform wind pressure distribution as predicted by [2], and represents the frame closest to the drive. As shown in figure 3, the specific cost of aluminum remains below that of steel for the range of aperture widths studied.

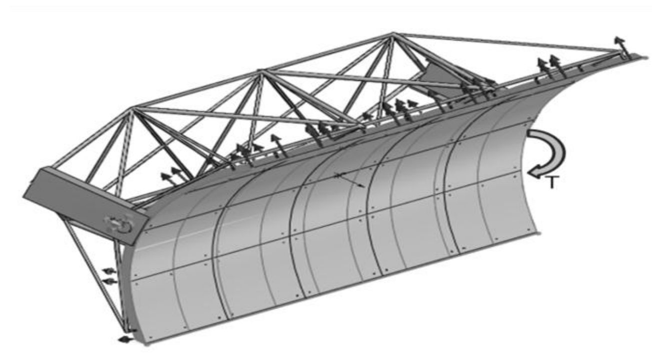


Fig. 2: Finite element diagram. SkyTrough frame geometry: non-uniform wind pressure load with torque from adjacent frames.

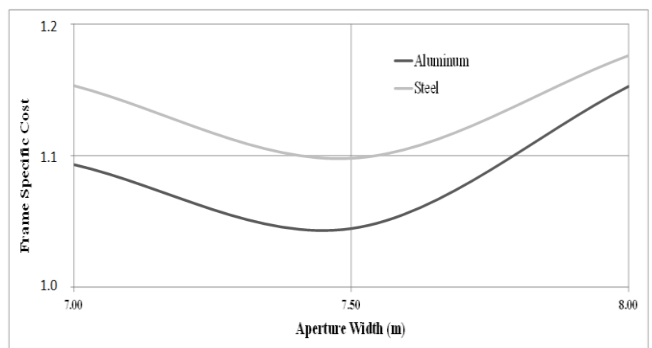


Fig. 3: Specific cost versus aperture width for steel and aluminum space frames.

As well as investigating a steel space frame, we examined a steel torque box and a steel torque tube. We also evaluated opposing dual cylinder drives as an alternative to the helical drive used on the SkyTrough. No paths to substantial cost reduction were identified with any of these alternatives, so optimization was focused on increasing the trough aperture, concentration ratio, operating temperature, and reflectance.

## 3. OPTIMIZATION

There are three major thrusts to LCOE reduction in this research: lower installed cost (primarily with an increase in SCA aperture area), increased outlet temperature (reducing the cost of storage), and increased reflectance and durability of ReflecTech. The relative cost impact of each task is shown in figure 4.

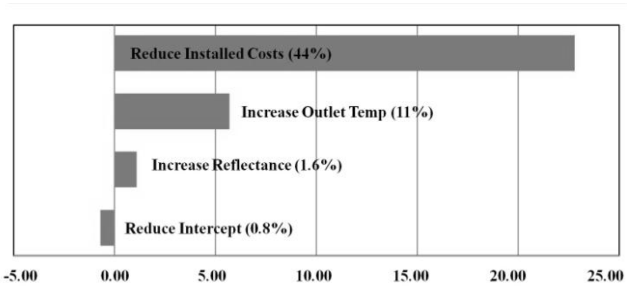


Fig. 4: The relative contribution of cost reducing measures. The negative impact of higher optical error associated with larger apertures is also shown.

An increase in trough size and concentration factor was a focus of our work. The only continuous, relatively independent parameter in these factors was aperture width. The real limit on increasing aperture width is the torsional load: the aperture area increases in proportion to aperture width, the torsional load increases in proportion to the square of width, and torsional load is the primary structural cost determinant in parabolic trough design. Our evaluation indicated that installed cost reduction would not be achieved at aperture widths above 9 meters.

Receivers of credible design and performance are manufactured for the parabolic trough market by companies that have already made substantial capital investment for high volume production. We limited our receiver investigation to selection of products offered by major suppliers: 0.070 meter diameter by 4.0 meter length, and both 0.080 and 0.090 meter diameter by 4.7 meter nominal lengths.

A single mirror module carries an integral number of receivers, and our evaluation considered 3, 4, and 5 receivers per mirror module. An SCA with a central drive has an even number of mirror modules. We ensured covering the optimum selection by evaluating five different mirror module counts per collector drive: 6, 8, 10, 12, and 14.

We defined 180 discrete cases for examination, shown in table 1, that spanned SCA aperture areas from 500 to 2900m$^2$, and concentration ratios from 80/π to 130/π. The aperture width was treated as a discrete, rather than continuous function, to simplify the analysis. We did selectively increase the resolution of our aperture widths at the conclusion of our effort, and found the optimums were relatively flat.

TABLE 1: OPTIMIZATION MATRIX

| | |
|---|---|
| Aperture width (m) | 7.0, 7.5, 8.0, 9.0 |
| Modules per SCA | 6, 8, 10, 12, 14 |
| Receiver size (m) | 0.070 × 4, 0.080 × 4.7, 0.090 × 4.7 |
| Receivers per module | 3, 4, 5 |

3.1 Cost

We executed designs for each of the components of the DSP parabolic trough for all described cases. Load was a primary design driver for many components; consequently, we also defined the loads for the range of optimization cases. Component quotations from the baseline SkyTrough were broken down into an indicative cost ($ per unit weight, area, etc.), and those indicative costs were used to define the cost per unit aperture for the DSP Trough.

The installed cost optimization results are graphically shown in figure 5.

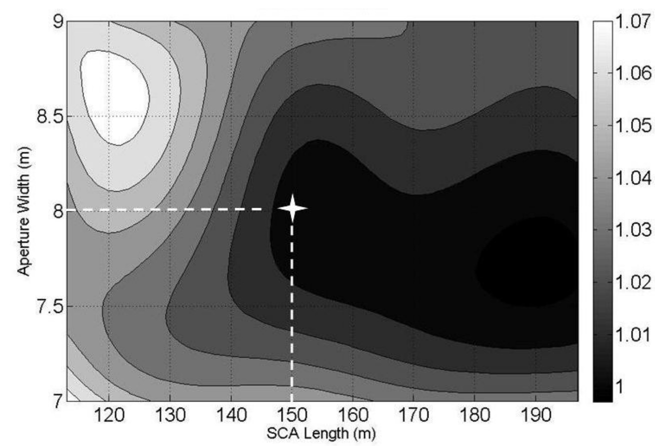


Fig. 5: Installed costs (normalized) for a high temperature parabolic trough as a function of aperture (0.080 or 0.090m receiver), including margins.

The performance of a parabolic trough is also affected by changes in size and concentration ratio. Our work also included development of an improved mirror film with increased reflectance. Installed cost was ultimately combined with performance to estimate the LCOE using the NREL System Advisor Model (SAM) [3]. The final optimum is shown in figure 5. The performance analysis is described in the following section.

3.2 Performance

The cost of a parabolic trough designed for utility applications is critical to our analysis; however, the performance must be established for each aperture case to select an optimum LCOE. SkyFuel used ASAP [4], an optical modeling program, to define the fundamental optical determinant in trough performance: intercept factor.

Performance estimates for the DSP trough were executed for each case in our optimization matrix. Specifically, we modeled sun shape, specularity, contour error, tracking twist, and receiver position error in ASAP ray trace models to define the geometric accuracy. In some cases, those estimates are dependent upon geometry (e.g., there is a direct relationship between aperture width and contour accuracy, as well as a relationship between SCA length and twist error). Sun shape, specular response, and tracking error are independent of aperture. Dependent errors were established for each case in our optimization plan.

ASAP allows combinations of probabilistic and deterministic errors in a single optical model that subsequently uses a ray trace algorithm to define the intercept factor. The model provides a more accurate representation of errors than Gaussian or other approximations, because it accounts for sensitivities to position on the parabolic surface.

No real mirror is perfectly smooth. Microscopic imperfections cause reflected light to deviate from a perfectly reflected beam to a slightly scattered reflected beam. This additional scatter in the reflected beam is characterized as the specular response in our models. ReflecTech, the silvered polymer film that provides the reflective surface in our analysis, demonstrates a surface with "specular error". The reflected intensity distribution can be accurately described by a circular, double Gaussian curve fit, as reported by Gee [5].

We selected a sun shape profile from Rabl [6], and a simple, two milliradian deterministic offset for tracking error.

We characterized the slope error of the DSP trough by manufacturing full scale mirror panels, supporting the panels in a representative space frame, and directly measuring the resulting error in the surface normal over hundreds of points on the reflective surface. Figure 6 shows the mirror panels of varying aperture width installed on a space frame.

The slope error as a function of distance from the vertex is presented in figure 7. These error terms are limited to a two dimensional case. We show the radial term for a 9m panel only. Slope errors in the longitudinal direction are not measured, and are an order of magnitude less important [7] than the two dimensional case shown for predicting parabolic trough performance.

The slope error data were used to construct a synthetic surface with a matching derivative field. We used the MATLAB [8] piece wise polynomial interpolation package, and performed the forward difference numerical differentiation:

$y(i+1) = m(i) \times h + y(i)$,
where m was the slope every h meters.

The piece wise interpolation was done for each slice, and we allowed ASAP to linearly interpolate the position of the surface between slices.


Fig. 6: Mirror panels of different aperture width installed on a space frame at the SkyFuel Development Test Center.

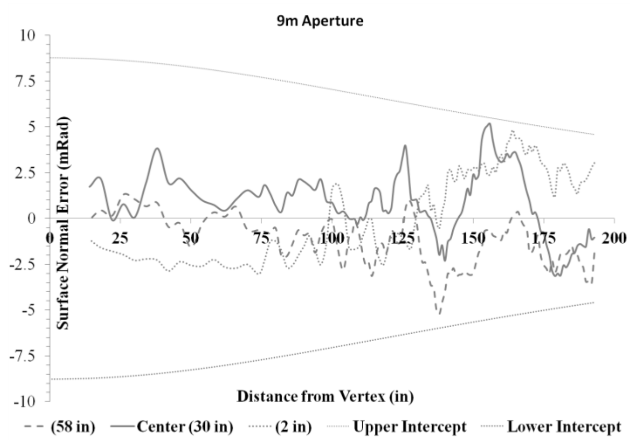


Fig. 7: Slope error versus distance from vertex at the center slice (solid line) and near the parabolic ribs (dashed and dotted lines) of a 9m aperture mirror panel. The vertical axis is slope error, in milliradians. The horizontal axis is distance from the vertex.

We have direct access to the wind speed, thermal output, and tracking orientation for the baseline SkyTrough on fifteen second intervals operating at the SEGS II solar power plant in Daggett CA for a complete year. We combined this data with the pitching moments developed by ASCE [9] to define an energy weighted average torsional load. The pitching moment was appropriately applied to the wind speed and tracking orientation at each time interval, multiplied by the energy output at the same interval, and subsequently divided by the sum of the energy output. The torsional load was adjusted based on aperture width for each case in our optimization matrix. A representative case is shown in figure 8.

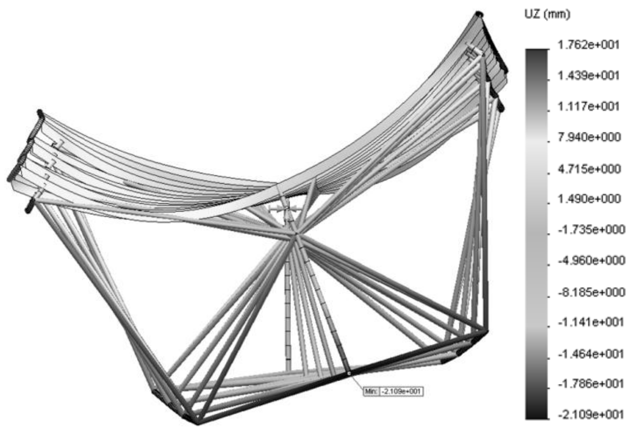


Fig. 8: Frame twist under energy- weighted torsional loads for one case in the optimization matrix.

The receiver is the target for reflected rays, and receiver diameter has a significant impact on the intercept factor for each case in our optimization matrix. The geometric accuracy term is plotted against aperture width for different receiver geometries in figure 9.

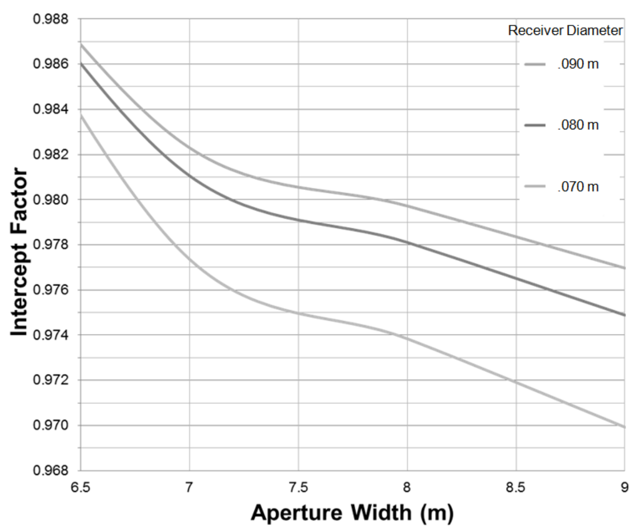


Fig. 9: Intercept factors produced from ASAP with the synthetic contour, receiver location error, sun shape, and specular distributions.

The relatively high intercept factors for the 0.080m and 0.090m receiver cases were a significant feature in our selection of optimum large aperture trough geometries.

4. RESULTS

We selected the NREL System Advisor Model to define LCOE, and entered the performance and installed cost data for each case in our optimization matrix. Financial inputs were held constant, and generally followed SAM defaults. The operating temperature was set to 500°C. Specific limits on fossil fuel use and storage cost estimates were described in the introduction of this paper. The minimum capacity factor was set to 75%.

The empirical SAM model was executed, and LCOE was minimized. The LCOE results as a function of aperture width and SCA length are shown in figure 10 for an 0.080m or0.090m diameter receiver.

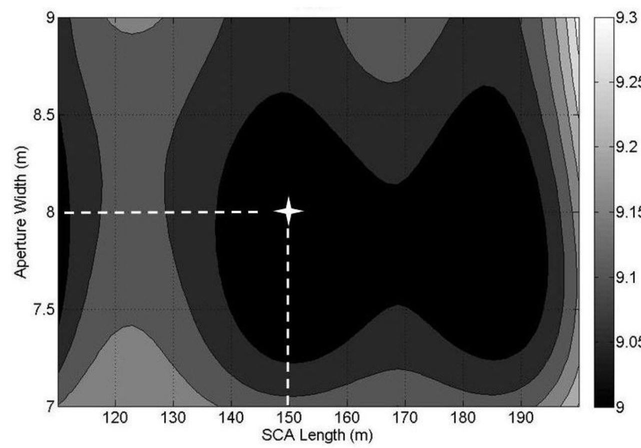


Fig. 10: LCOE as a function of aperture width and SCA length.

The LCOE plot has two distinct areas of optimization. The first region occurs at an SCA length of 150m, only achieved by the 4 receiver - 8 mirror modules case. The second optimum at 188m SCA length is achieved by both the 4 receiver - 10 modules and the 5 receiver - 8 modules cases. We chose the first optimum zone because the total torsional demands on the drive in this region are within the current manufacturing capacities of the drive vendors.

During the course of our analysis, we reached the following general conclusions:

- Reduction in installed cost provides the largest potential for reductions in LCOE.
- Increasing operating temperature from 400°C to 500°C is secondary to installed cost. Cost reductions associated with increased operating temperature are the result of lower storage cost.

- The regions for aperture optimization are broad, with no significant distinction between 7.5m and 8m aperture width, or 150m and 180m SCA lengths.

Our specific conclusion: a parabolic trough optimized for utility applications is larger, and operates at higher temperature, than the current state-of-the art collectors. The anticipated LCOE, with optimum troughs, falls below $0.09/kWhe.

## 5. ACKNOWLEDGMENTS

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