Achievement of the $100/m^2 Parabolic Trough

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Abstract. It has long been a goal of the Concentrating Solar Power (CSP) industry to supply parabolic troughs for electricity generation for less than $100/m^2. This benchmark has now been achieved, with a product that is available for commercial delivery in 2018. After years of continued development, research support from the US Department of Energy (DOE), and a shift to a global supply chain, SkyFuel® has now achieved a Cost of Goods Sold (COGS) for the SkyTrough® DSP parabolic trough collector of less than $100/m^2 (2017 US Dollars).

This achievement required a holistic approach to parabolic trough analysis, with the development effort based on efficiency analyses, material indices, labor rates, manufacturing and assembly methods, and worldwide supply chain logistics. The following text describes in detail the base assumptions, optimization strategy, component design, manufacturing approach, and supply chain logistics undertaken to achieve this goal.

As a result of the analyses, the primary material of construction changed from aluminum to steel. The aperture of the trough increased from six to seven meters, and extended to a total collector length of 146 m. There are four receivers per module, each 4.51 m long by 80 mm diameter, and eight modules in a Solar Collector Assembly (SCA). After analyzing torque tubes, torque boxes, and monocoque structures as a comparison, a space frame design was selected as the primary structural support; however, the frame has been reduced in relative size and has assumed a new geometry. The trough's reflective surface was also assessed against thick glass mirrors, thin glass mirrors, composite stacks, and thin-film polymer reflectors. A thin-film polymer reflector was selected as the reflective surface, due to its low cost of materials and savings from shipping and installation.

This collector is designed for use with a variety of working fluids including molten salt, with an outlet temperature of up to 565°C. Use of molten salt as the collector working fluid reduces storage volume, improves plant efficiency, and allows for operation in parallel with fossil-fueled boilers for hybridized utility-scale power applications. It has built-in electrical isolation and salt-compatible flexible piping connections, a reduced-cost drive system, and a parabolic rib design that contributes to its high efficiency and low cost. This publication documents the fundamental approach taken to achieve a COGS of $100/m^2, detailing the methods used in the analysis and the unique characteristics of the resulting product.

BACKGROUND AND ASSUMPTIONS

SkyFuel is a company dedicated to the design and implementation of parabolic trough equipment for solar power generation and process heat applications. In 2010, the National Renewable Energy Laboratory (NREL) tested the SkyTrough parabolic trough collector, and found that it performs with an optical efficiency of 77.3% [1]. This efficiency was achieved with a highly-reflective polymer film reflector and a collector that does not require manual adjustments or assembly buildings. Now the design has been adapted to a larger-aperture, lower-cost parabolic trough collector. SkyFuel began its SkyTrough DSP development under a DOE cooperative research agreement in 2010. In 2013, a report [2] was published at SolarPACES detailing the approach taken for the design of a trough that optimized both performance and cost. The optimization method established by that report became the basis for the design of this collector, and with the same focus on quality, reliability, and optical efficiency, the cost of this utility-scale parabolic trough collector has been reduced to under $100/m^2$.

The new design of the SkyTrough DSP increases the strength of the frame, mirrors, and structural members while reducing component cost. Nearly all components were designed for a Chinese supply chain, and the hydraulic drive system underwent a complete redesign to reduce weight while maintaining tracking accuracy and performance. Every component in the SCA was optimized for the larger aperture and was fully analyzed for cost and performance.

Unlike alternate low-cost troughs on the market, the SkyTrough DSP was developed specifically for highly-efficient power generation on a utility scale. It is designed to operate with a bulk fluid temperature of up to 565°C. This high temperature operation enables cost-effective thermal storage for power delivery in periods of low solar irradiance and can increase thermal-to-electric conversion efficiency.

Wind loads for the structural analysis were based on regions in northern and central China where CSP is expected to be prevalent, and equate to a 3-second gust with a Mean Recurrence Interval (MRI) of 50 years or greater. While the previous-generation collector was designed for gusts of up to 37.5 m/s (84 mph), the SkyTrough DSP will withstand gusts of 40 m/s (90 mph) or greater without significant damage. So, while the SkyTrough DSP has been reduced in cost, it is also more robust than previous platforms. All components in the SkyTrough DSP have been designed with coatings that guarantee a minimum lifetime of 30 years in the field.

EFFICIENCY AND SYSTEM DESIGN

At the outset of the design effort, a decision was made to maintain the high efficiency of the previous product, and a design goal of 76% was set for optical efficiency. Many low-cost parabolic troughs have been designed for process heat applications and suffer reductions in efficiency that are not suitable for utility scale electricity generation. Figure 1 presents the relationship between efficiency and solar field cost on a square-meter basis for electricity generation, which yields an average value of $3.76/m^2$ for each point of efficiency. This data was derived from analyses performed using the System Advisor Model (SAM) published by NREL. In the study, the Levelized Cost of Energy (LCOE) was maintained constant, while optical efficiency and cost were iteratively reduced and the system re-optimized. Each data point presents the optimum solar field size and storage volume for a given optical efficiency, with only the solar field cost adjusted to maintain LCOE. In the SkyTrough DSP design effort, a reduction of $50/m^2$ was achieved for only a 1% reduction in optical efficiency, an order of magnitude greater than the baseline identified by the efficiency study. Comparatively, a parabolic trough with 72% optical efficiency would require a COGS of $85/m^2$ to match the LCOE of this design, and a trough with an optical efficiency of 68% would require a cost of $70/m^2$. The design

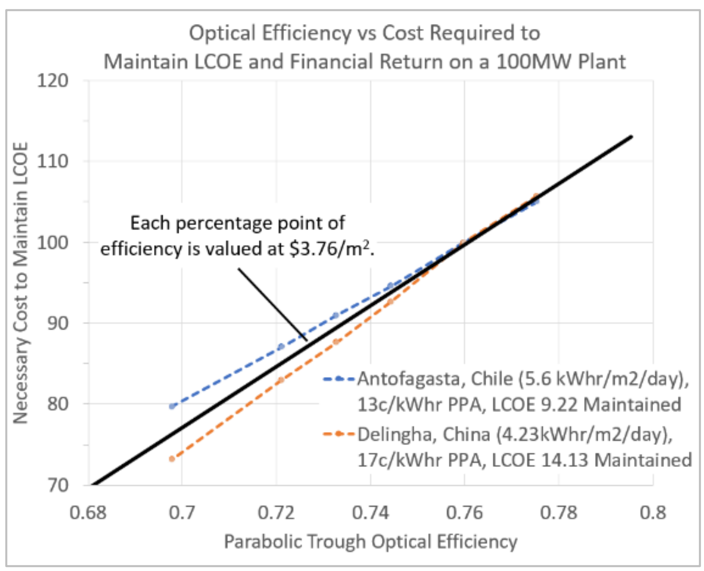

FIGURE 1. Optical Efficiency Required to Maintain LCOE and Financial Return on a 100MW Plant

optimization for this product was performed with this cost/performance metric in mind, in such a way that cost reduction did not adversely impact efficiency. While the design changes and sourcing decisions made to date have each exceeded the cost/efficiency benchmark of $3.76/m^2, the holistic approach taken in this effort has identified the vast majority of cost reduction opportunities, and further gains from this point that achieve the same metric will be challenging to realize.

In the design optimization of 2013 [2], assumptions led to a 90 mm x 4.72 m receiver tube, an aperture of 7.6 m, and a collector length of 150 m. Since that time, receiver prices have dropped substantially, which has pushed optimization toward a comparatively lower aperture. However, these same lower-cost receivers have also yielded a reduction in thermal efficiency, which tends to push designs toward a higher concentration ratio to reduce heat loss. This new receiver information was input to the optimization model of 2013, and resulted in a new optimum aperture of 7.0 m, with a receiver diameter of 80 mm and a collector length of 146 m. The results of this study are presented in Figure 2. Material cost and availability drove the selection of the receiver length to 4.51 m, reduced from 4.7 m in 2013. A 2014 paper [3] presented the optical efficiency of the 7.6 m trough, which exceeded expectations and allowed for a reduction in receiver diameter from the originally-designed 90 mm tube. This reduction has a small net benefit to capital cost, but greatly increases plant performance due to the concentration ratio increase and corresponding reduction in heat loss.

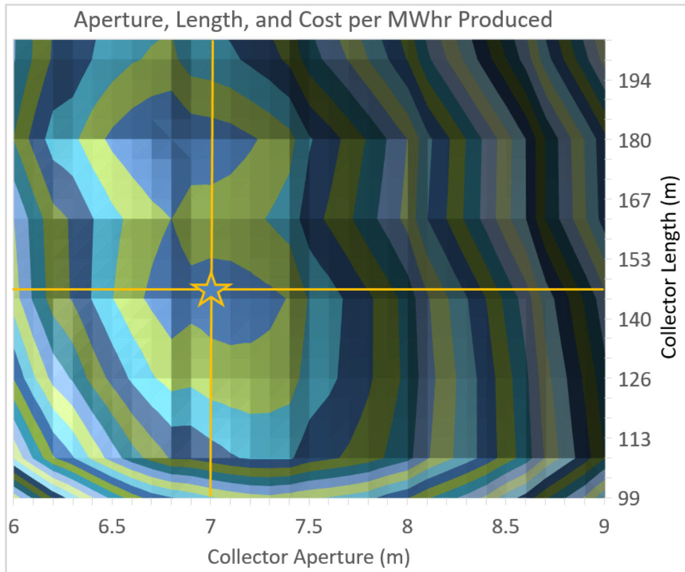

FIGURE 2. Result of System Design Analysis, Yielding an Optimum Collector Size of 7m Aperture x 146m Length

MANUFACTURING, SUPPLY CHAIN, AND LOGISTICS

To take full advantage of China's 10GW CSP initiative in their 13th Five-Year Plan [4], a strategic decision was made to fully develop a supply chain in China to supply Chinese-based projects. This choice led to a reevaluation of materials indices and fundamental assumptions inherent in parabolic trough design. Historically, SkyFuel has chosen aluminum as its structural material, but has based that decision on material properties and the associated costs of a supply chain based in the United States. Moving sourcing to China provided a cost reduction across the board, but the reduction is not consistent among materials. The US Department of Commerce currently issues dumping margins and subsidy rates on aluminum [5] and steel [6] imports from China. When compared to US-based pricing, these duties indicate that cost reduction is up to 22% greater for Chinese steel than it is for Chinese aluminum. Figure 3 presents this difference and the impact that it has on the material decision for product design.

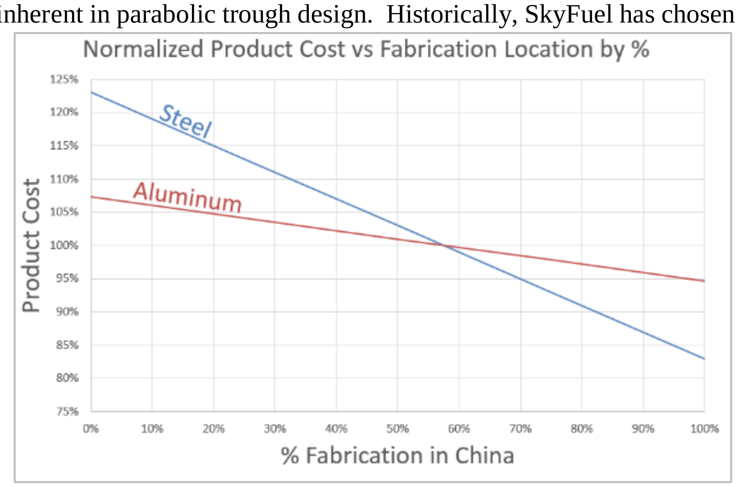

FIGURE 3. Cost Reduction Percentages for Steel and Aluminum with a Chinese Supply Chain

With the selection of steel, components utilize roll-form and progressive stamping manufacturing methods to provide economic advantages and mass-scale production. Worldwide, these methods are some of the most common and automated, making them low cost and widely available. Using pre-coated steel coil and advanced coil line technologies, components are manufactured more quickly, more accurately, and with reduced scrap rates. Labor and handling expenses are significantly reduced, and parts have higher consistency. The change from American aluminum to Chinese steel has resulted in a 70% cost reduction in select components.

The receiver tubes account for roughly 25% of the cost of a concentrated solar collector, and in the 2013 study, molten salt receiver tubes were expected to cost $28/m^2, with projected reductions of up to 25% by 2017. With receiver tube manufacturing relocated to China, however, prices are now estimated at nearly 50% the price they were in 2017. The expanding market for parabolic trough receivers has also provided more options in receiver length, allowing improved collector optimization, reduced thermal losses, and ultimately, a lower cost per unit length.

While not directly related to the COGS, consideration was made to minimize shipping and field assembly costs. By bolting together torque plate components, drive pylon sections, and rib halves in the field, even the largest components achieve maximum packing density and minimized shipping costs. These sections bolt together without the need for large assembly stations in the field. In 2015, NREL published a cost analysis [7] which independently assessed the costs for both a SkyTrough SCA and a traditional glass facet SCA. For a commercial scale installation of 100 MW_e, a substantial assembly station was required for the glass facet SCA, amounting to an estimated $10/m^2 in increased capital cost. The use of precision ribs with slide-in mirror panels and blind, quick-pull rivets does not require an assembly station in the field. The SkyTrough DSP employs these assembly methods in a manner that maintains the high-precision components and meets all optical accuracy and performance expectations.

COMPONENT OPTIMIZATION

Throughout the design of the SkyTrough DSP, each component was analyzed for both cost and performance, with the goal of maintaining a $100/m^2 COGS. The following sections describe the steps taken for each of the major subassemblies of the parabolic trough, including the frame, reflectors, parabolic ribs, and drive system. Finally, protective coatings are examined, as they are fundamental to each of the component designs. The result of this design-to-cost exercise is a highly efficient and low cost solar collector suitable for the utility-scale power market.

Frame

The frame of the collector is the primary carrier of wind-induced torque, and structurally supports the optical surface. As it typically accounts for about 25% of the cost of a parabolic trough, many approaches have been taken to reduce the cost. In the evaluation of this collector, weight and stiffness were analyzed for various frame designs including torque tubes, torque boxes, monocoques, and space frames. Across all designs, frame width and weight are inversely proportional; as the frame width decreases, the weight of the frame increases to carry the required torque. However, considering the extended length of space frame members in a large-aperture trough, buckling and fatigue become governing factors in the analysis. Considering the frame styles presented above, the space frame proved to be the most efficient design, however it yielded an optimum frame width that was less than the collector aperture. Equal length members were used to improve field assembly time, reduce packaging requirements, and optimize shipping. They also provided tooling savings, and reduced part count. As a result, a new, patent-pending space frame geometry with exceptional torque-carrying capacity was implemented.

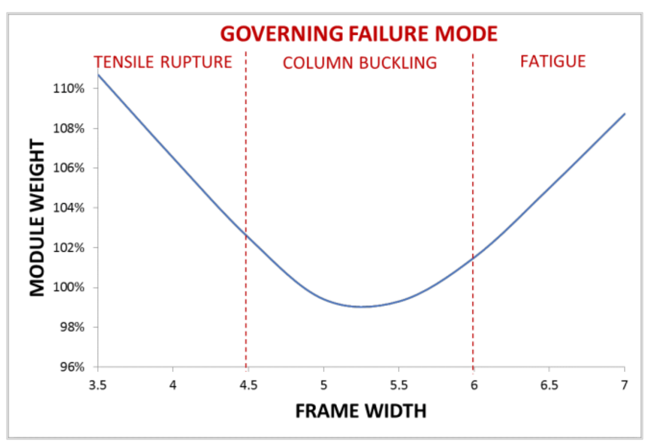

FIGURE 4. Frame Width vs Module Weight, Presenting Governing Failure Mode

In the previous generation of this product's design, wind-induced fatigue governed the design of the 6 m frame, and safety factors for other failure modes were unnecessarily high. By reducing the length of the members and switching to steel, fatigue is no longer the limiting failure mode. The module is designed more efficiently and with more traditional safety factors for other failure modes. As presented in Figure 4, the trough's weight is reduced with a 5 m width frame, where column buckling is the governing failure mode.

With the switch from aluminum to steel, the frame member connecting nodes are now made as die stamped parts, as opposed to extruded aluminum. Thin sheets of steel can be accurately stamped into the required shapes, and nesting of the pieces reduces scrap. Drawn edges add strength and stiffness to the parts without increasing material thickness, and the final assemblies are riveted and welded together at the manufacturer to maintain the high accuracy required for optical efficiency.

With about 25% of the collector cost coming directly from the frame, it was integral to the cost reduction process to use a lightweight structure for the trough. The patent-pending geometry maintains the required torsional stiffness while using fewer unique parts, and combined with lighter-weight structural members, effectively reduced the cost of the frame by 47% on a m^2 basis.

Reflectors

As with previous generations, the SkyTrough DSP maintains the use of ReflecTech mirror film as the reflector surface for the trough. The film is laminated onto thin metal sheets to form the mirror panels, which have advantages over glass mirrors as they are virtually indestructible, allow for rapid installation, and require fewer structural support elements. In the initial product optimization phase of this design effort, ReflecTech mirror panels were analyzed against glass facets to establish the most economic choice. As described in NREL's parabolic trough cost analysis [7], the supporting structure for traditional glass mirrors is 37% heavier than the structure required to support ReflecTech mirror panels.

Changing the reflector's lamination substrate from aluminum to steel provides additional savings on top of the cost demonstrated by NREL. The mirrors are designed to prevent plastic buckling from occurring during high wind events; for an aluminum panel, a thickness of 1.2 mm was required to prevent buckling with a 6 m aperture. For a 7 m aperture, a steel panel thickness of 1.2 mm proved to be more material than required. As presented in Figure 5, reducing the steel panel thickness to 1.0 mm provided improved buckling resistance even with an increased aperture. This reduction in thickness saves an estimated 1.6 kg of steel per square meter of mirror surface.

As a result of the material change and supply chain in China, the reflector panels have reduced in cost by 32% on a m^2 basis.

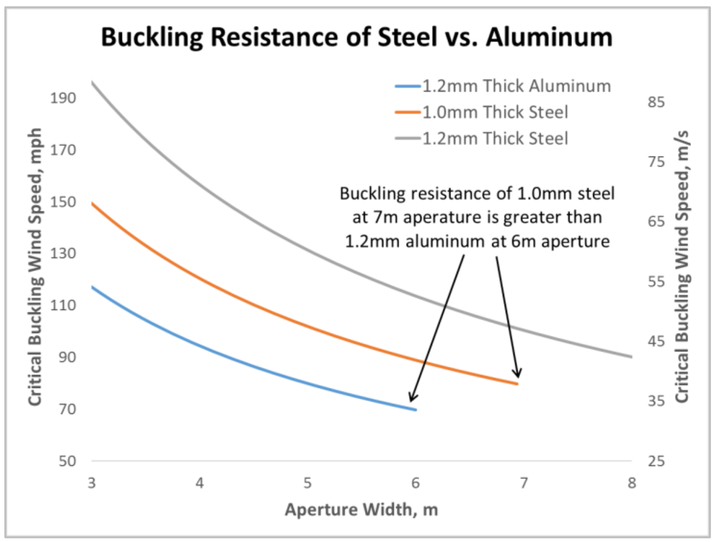

FIGURE 5. Buckling Resistance of Steel and Aluminum Reflector Sheets as a Function of Aperture and Wind Speed

Parabolic Ribs

Parabolic ribs support the reflector panels, provide the backing for the precise parabolic optical surface, and connect the reflector panels to the space frame. In competing glass-based collectors, the parabolic ribs are synonymous to the cantilever arms that support the glass panels. Cantilever arms can account for as much as 1/3 the cost of a parabolic trough [7], but due to the extended width of the SkyTrough's space frame, the parabolic ribs account for less than 10% the cost of the collector. When modified from a full-width frame to one with partially-cantilever rib supports, the rib became more structurally significant than in prior designs. The rib now carries a significant moment at the outermost frame connection, and must support the reflector as a cantilever load near the rim of the collector.

Optimization of the rib was dependent on both minimizing weight and developing the design for manufacturing. To determine the minimum required strength of the rib, wind loads were calculated from NREL's Wind Tunnel Tests of Parabolic Trough Collectors [8]. As presented in Figure 6, applying the worst-case loading configurations to the rib in the form of a pin-supported indeterminate beam, shear forces and moments are carried through the structure. The maximums and minimums from all combined data sets defined the parameters for the design of the rib components. Based on the American Institute of Steel Construction code [9], the necessary rib web width and thickness was calculated to prevent flexural yielding, lateral-torsional buckling, and flange/stem buckling of the member from the applied wind loads.

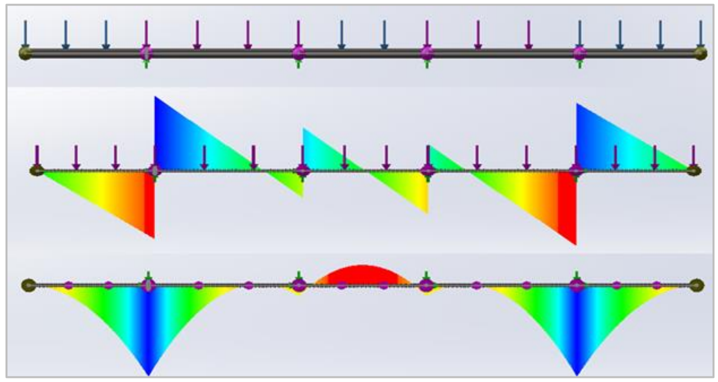

FIGURE 6. Parabolic Rib Loading Condition and Resulting Shear and Moment Diagrams

With the minimum structural requirements determined, the web components were nested based on coil fabricator recommendations for low-cost and common width. Because little to no savings is realized from scrap material, the resulting gaps between ribs were included within the rib web for additional stiffness and accuracy during collector operation. Figure 7 presents the nesting profile for each of the rib components, as well as the fully-assembled rib.

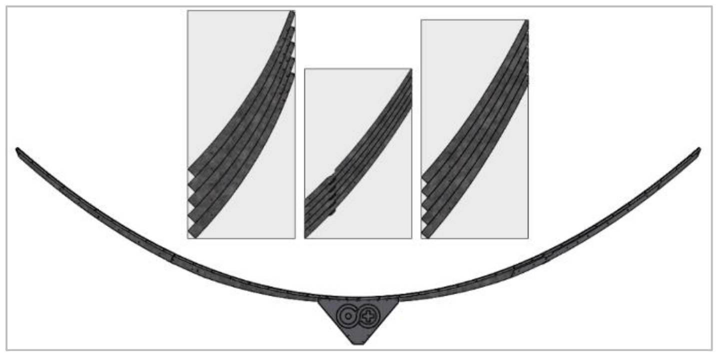

FIGURE 7. Parabolic Rib Nesting Profile and Final Assembly

Finite element analysis was performed on the rib to ensure that deflection and slope error were minimal during operational wind loads. The result was a structurally sound, partial-cantilever rib, manufactured by automated blanking from pre-coated steel coil. While this rib is larger, withstands higher loads, and is more structurally significant than the rib of the previous SkyTrough design, the cost per square meter reduced by over 60% overall.

Drive System

A parabolic trough's drive system acts as the motive force to position the collector toward the sun, track throughout the day, and return the collector to stow at the end of the day or during periods of inclement weather. As the single point of rotational stability, the holding torque of a drive system can be significant in utility-scale collectors. While many drive mechanisms have been implemented for smaller parabolic troughs in the past, nearly all utility-scale troughs rely on hydraulic pressure to position and hold the collector rotationally.

SkyFuel holds a patent on the use of helical hydraulic actuators for use in parabolic trough systems [10], but commercial availability limits the use of helical actuators to a holding torque of about 225 kN-m. Sourcing a larger unit for the SkyTrough DSP had limited options, high cost, and increased risk. Instead, a classical dual cylinder drive design was adopted, but with a unique cylinder positioning arrangement that reduced overall loads by 15% compared to traditional designs.

The drive pylon is the steel structure that supports the hydraulic system. It resolves wind loads, gravity loads, and the hydraulic reaction loads from the cylinders to the ground. Consequently, the optimization of the pylon system is a balance between the cost of the structural frame and the cost of the hydraulic system. Using a dual-cylinder hydraulic system, increases in bell-crank arm length decrease the hydraulic cylinder forces required to generate the same actuation and holding torques. With reduced hydraulic loads, the longer cylinders transmit the forces closer to the ground, reducing the structural requirements of the pylon. A longer bell-crank arm also increases the range of motion, but requires longer hydraulic cylinders to achieve full rotation of the collector. Longer hydraulic cylinders increase the capital cost of the cylinders, reservoir, pump, and fluid, as well as the operational cost associated with parasitic electrical load. With an increased stroke length, larger cylinder diameters are also required to prevent compression buckling of the rod portion of the hydraulic actuator. A relationship was developed between the hydraulic system cost and the structure cost to determine the optimum hydraulic stroke length for this design. For the SkyTrough DSP collector, a stroke length of 830mm was chosen. Figure 8 presents the relationship between cylinder stroke and drive pylon system cost, noting the increase in pylon weight with reduced-stroke cylinders, and the increase in hydraulic system cost with longer cylinders. Note that the cylinder lengths in this arrangement are only accurate for the specific set of loads associated with the SkyTrough DSP collector. Alternate apertures and cylinder mounting locations may produce varying results, but are expected to follow a similar trend.

To determine pylon reaction loads, hydraulic requirements, and optimum bell-crank angles, wind loads were calculated from NREL's Wind Tunnel Tests of Parabolic Trough Collectors [8] in conjunction with Chinese wind code GB50009 [11] and American Society of Civil Engineers (ASCE) 7 [12]. Trigonometric relations were developed to define reaction angles and loads occurring between the frame, hydraulic cylinders, and bell-crank arms for all collector operation angles with both directions of actuation. The required holding forces for survival wind loads with isolated hydraulic cylinders were then calculated for stow angle requirements. Every combination of allowable bell-crank arm angles was analyzed to determine which combination resulted in the lowest hydraulic load. By minimizing the hydraulic loads, the hydraulic power system, structural frame, and bell-cranks were reduced by 35% on a m^2 basis compared to previous designs.

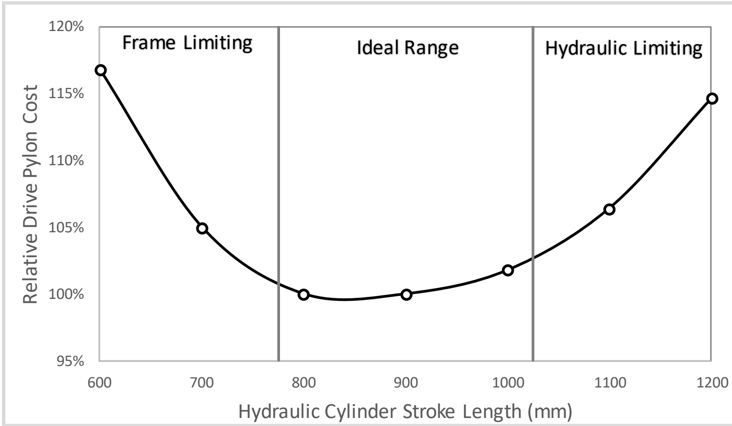

FIGURE 8. Optimization of Hydraulic Drive System

Coatings

Utility-scale parabolic trough collectors are typically designed for service lives of 25 years or more, in environments with highly-variable conditions. They may be exposed to saline environments in coastal regions, abrasive environments in desert sand storms, or corrosive environments in hybrid power plants and industrial process applications. Ambient temperature may vary from -20°C in the winter to over 50°C in the summer, and the surfaces are routinely exposed to high-pressure wash cycles to maintain the cleanliness of the reflective surfaces.

The choice of a steel material of construction required the selection of appropriate coatings to ensure service life and appearance of the product. Because paint cannot meet system service life expectations, galvanic protection of the steel is necessary. As presented in Figure 9, the zinc hot dipping process, applied after fabrication, can achieve coating thicknesses surpassing 70 microns which yield life expectancies greater than 50 years in industrial and marine environments. However, dipped parts must be at least 3mm thick to avoid significant warping. Pre-coated zinc galvanized coil rarely exceeds 20 microns thick per side (Z275) which is insufficient as a standalone coating. While a secondary paint layer is routinely applied over the zinc to provide physical protection, only the high-cost polyvinylidene fluoride (PVDF) provides

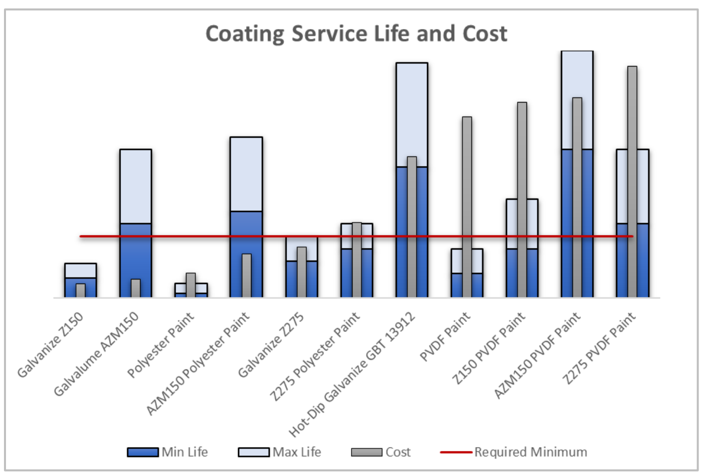

FIGURE 9. Coating Service Life and Cost

sufficient protection for extended life. Instead, a thinner layer of 55% aluminum-zinc (55AlZn) provides both galvanic and physical protection for a substantially lower price. The galvanic protection from the zinc can only sufficiently protect steel within 1.0-1.5 mm, so when the material edge is greater than 2.0 mm thick or the coating is removed for welding, a remetalizing or zinc hot-dip coating must be applied. The SkyTrough DSP was designed to utilize pre-coated 55AlZn coil, 55AlZn welded and remetalized tube, and hot-dipped zinc heavy-wall structural weldments to minimize coating costs while providing superior product protection. As a result, while the previous aluminum trough required no coating at all, the combination of low-cost steel and extended-life coatings resulted in an overall material price reduction.

CONCLUSIONS

Through design optimizations, material and manufacturing analyses, and a switch to a global supply chain, the SkyTrough DSP has achieved the target of $100/m^2. It maintains a high thermal efficiency, high concentration ratio, and large aperture, setting a new benchmark for the CSP industry. In addition to the $100/m^2 COGS, the design leverages local manufacturing and assembly, requires minimal sunk investment in field assembly equipment, and allows for rapid and unskilled field assembly.

This achievement has not been realized at the expense of performance; rather, the SkyTrough DSP will maintain an optical efficiency of 76%, which can be valued at $15/m^2 when compared to the efficiency of many competitive utility-scale parabolic troughs on the market. It is larger, stronger, and more wind resistant than previous designs, and an additional savings of up to $10/m^2 is evident in the innovative field assembly methods of the SkyTrough DSP. These combined improvements make the SkyTrough DSP a true step-change in the market for parabolic trough systems. The SkyTrough DSP is available for commercial delivery in 2018.

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