Parabolic Trough Collector Cost Update for the System Advisor Model (SAM)

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National Renewable Energy Laboratory

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Acronyms

ATS	advanced thermal systems (heliostat)
BOM	bill of materials
CSP	concentrating solar power
DOE	U.S. Department of Energy
DFA	design for assembly
DFM	design for manufacturing
DFMA	design for manufacturing and assembly
EPC	engineer, procure, construct
HTF	heat transfer fluid
ITC	Investment Tax Credit
LCOE	levelized cost of energy
NREL	National Renewable Energy Laboratory
OD	outer diameter
PPA	power purchase agreement
SAM	Solar Advisor Model
SBP	Schlaich Bergermann und Partner, Sonne GmbH
SCA	solar collector assembly
SCE	solar collector element, aka module
SF	solar field
TES	thermal energy storage

Executive Summary

This report updates the baseline cost for parabolic trough solar fields in the United States within NREL's System Advisor Model (SAM). SAM, which is available at no cost at https://sam.nrel.gov/, is a performance and financial model designed to facilitate decision making for people involved in the renewable energy industry. SAM is the primary tool used by NREL and the U.S. Department of Energy (DOE) for estimating the performance and cost of concentrating solar power (CSP) technologies and projects.

The research team performed a bottom-up build and cost estimate for two state-of-the-art parabolic trough designs—the SkyTrough and the Ultimate Trough. The assumed solar field area in both cases was about 1.1 million square meters—the equivalent of a large CSP plant. The SkyTrough analysis estimated the potential installed cost for the solar field at $\$170/m^2$. The investigation found that SkyTrough installed costs were sensitive to factors such as aluminum alloy cost and production volume. For example, in the case of the SkyTrough the installed cost would rise to nearly $\$210/m^2$ if the aluminum alloy cost was \$1.70/lb instead of \$1.03/lb. Accordingly, one must be aware of fluctuations in the relevant commodities markets to track system cost over time. SkyTrough uses a reflective polymer film sold under the name ReflecTech PLUS.

The estimated installed cost for the Ultimate Trough was only slightly higher at $\$178/m^2$, which includes an assembly facility of \$11.6 million amortized over the required production volume. Considering the size and overall cost of the Ultimate Trough solar field, two parallel production lines in a fully covered assembly facility—each with the specific torque box, module, and mirror jigs—would be justified for a full CSP plant. For comparison, the developer estimated that for a solar field of roughly 40% of the NREL-assumed size using synthetic oil for the HTF the module assembly line was on the order of €5M (~\$6.7M). The steel-framed Ultimate Trough solar field cost was more sensitive to steel prices than the SkyTrough. Ultimate Trough uses back-surface glass mirrors.

The greater level of detail available for the analysis and the further commercial development associated with the SkyTrough led to its selection as the new default parabolic trough within SAM's Physical and Empirical Trough Models. Relative to NREL's 2010 study of a commercial-scale CSP parabolic trough reference plant, the SkyTrough installed cost was approximately 43% lower than the previous value (C. Turchi 2010) and 37% lower than the revised number from 2012. If one adjusts for different cost years (the prior numbers were based on 2009 and 2010 dollars), the reduction in cost is even more significant. There are several factors, including the overall design development of parabolic trough technology that have attributed to the decreased installed costs over time. For example the SkyTrough utilizes single, lightweight reflector panels that slide into place, rather than the previous reference trough design that required two heavy glass mirror panels with multiple attachment points. The SkyTrough utilizes fewer parts and has simpler assembly steps. With lighter reflector panels, a stiff, lightweight spaceframe instead of a steel torque box is used. The SkyTrough also has been designed to use lighter materials such as aluminum, so the overall component weights are further reduced.

The Ultimate Trough can be considered the next generation of the commonly utilized EuroTrough. The Ultimate Trough has sought to reduce costs by building larger individual collector modules and therefore utilize significantly fewer parts per collector assembly and also it requires fewer foundations to be installed relative to previous NREL references.

Other non-solar-field costs within SAM were updated by indexing for inflation. Changing these values in SAM's current default Physical Trough Model leads to a change in the estimated real levelized PPA price from 14.9 ¢/kWh to 13.9 ¢/kWh. Note that the SAM default case includes a 30% investment tax credit (ITC).

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1 Introduction

Concentrating solar power (CSP) technologies capture the heat of the sun to drive a thermo-electric power cycle. The most common CSP technology uses parabolic trough collectors. Trough power plants have large arrays of solar collectors that feature a reflective surface curved in the shape of a parabola (or trough) to focus sunlight onto a receiver pipe (Figure 1). A heat-transfer fluid (HTF), which is often synthetic oil, flows through the receiver and is heated by the absorbed sunlight. This hot fluid is used to generate steam that turns a conventional steam turbine/generator to produce electricity. The spent steam from the turbine is condensed into water and recirculated by feedwater pumps to be transformed back into high-pressure steam.

Wet, dry, or hybrid cooling can be used to cool and condense the spent steam; the selection will influence water consumption, cycle performance, and cost. A parabolic trough plant is composed of the following subsystems: solar collector field, receiver and associated HTF system, power block, thermal storage (optional), fossil-fired backup (optional), and necessary ancillary facilities (see Figure 2).

Figure 1. Parabolic trough collector and receiver tube.

Photo from SkyFuel Inc., NREL 16604

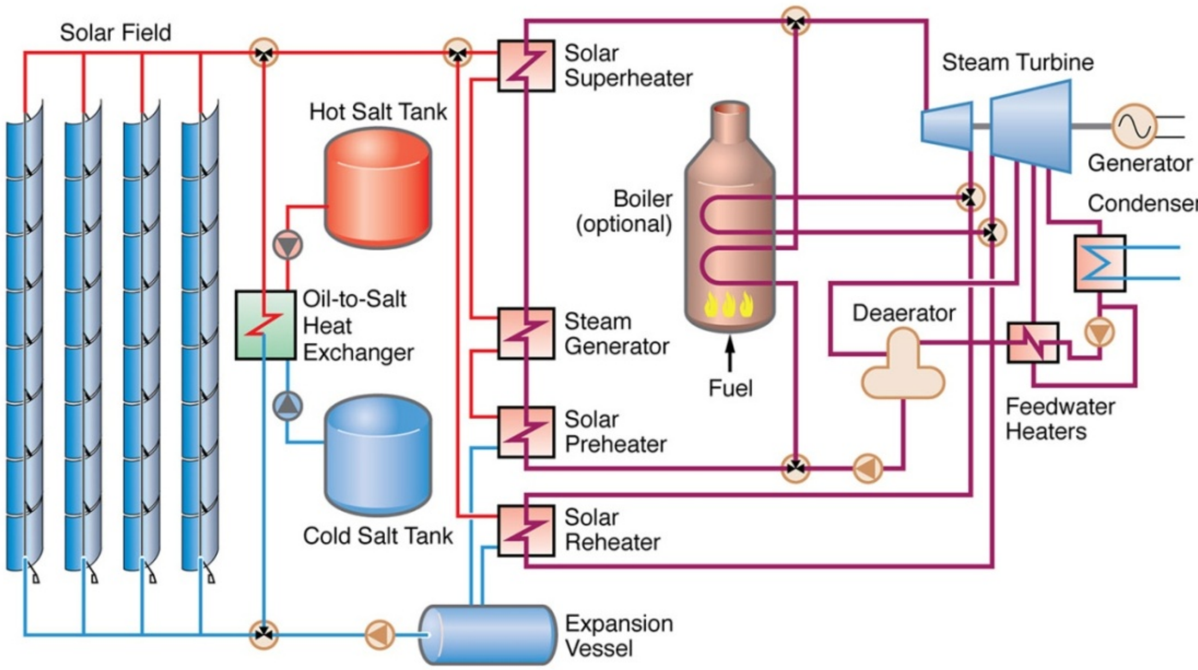

Figure 2. Simplified schematic of a parabolic trough power plant.

Illustration by EPRI (EPRI 2010)

2 Background and Motivation

2.1 Prior Analyses

In 2010, NREL established a baseline cost for parabolic trough technology in the United States by designing and costing a 100-MW parabolic trough plant with six hours of thermal energy storage (TES) (C. Turchi 2010). The project was a joint undertaking between NREL and WorleyParsons Group. In 2013, a similar study (C. S. Turchi and Heath 2013) was published to establish the baseline for the molten-salt power tower technology in the United States. This February 2013 report utilized the older 148 m^2 Advanced Thermal Systems (ATS) heliostat design as documented in (Kolb et al. 2007). The ATS heliostat design was also used as the baseline in DOE's 2010 Power Tower Roadmap (Kolb et al. 2011). In November 2013, NREL provided DOE with an update to the estimated cost of a molten-salt power tower that included a cost estimate for BrightSource Energy's LH-2.2 heliostat design that is deployed at the Ivanpah Solar Electric Generating System (C. S. Turchi et al. 2015).

This report updates the assumed design and baseline cost for parabolic trough solar fields in the United States—much as the work listed above updated those values for heliostat fields. The results of this analysis are used to update default cost data provided for parabolic troughs within NREL's System Advisor Model (SAM). SAM, which is available at no cost at https://sam.nrel.gov/, is a performance and financial model designed to facilitate decision making for people involved in the renewable energy industry. SAM is the primary CSP performance and cost tool used by NREL and the DOE to evaluate CSP technologies and projects.

2.2 Troughs in the Marketplace

Despite the emergence of power tower systems, the CSP landscape is still dominated by parabolic trough systems. According to the latest CSP Today's Global Tracker[1] (CSP Today 2015), the United States is home to six power tower projects totaling 536 MW_e and 19 trough projects totaling almost 1600 MW_e. Worldwide, trough plants and projects outnumber power towers by 76 to 15. The activity in parabolic trough projects indicates that this technology is still active in the marketplace and has benefited from design improvements and cost reductions that warrant an update within NREL's and DOE's cost analysis. Furthermore, the potential of deploying molten salt as the solar field HTF and TES media would allow troughs to more effectively compete with power tower systems (C. S. Turchi et al. 2015).

2.3 Selection of SkyTrough and Ultimate Trough

The objective of this report is to provide an update to parabolic trough solar field costs provided in NREL's 2010 study (C. Turchi 2010). While most trough designs continue to rely on back-surface curved-glass mirrors, reflective polymer films and front-surface glass designs have been proposed and developed. The study only considered available commercial designs and selected a reflective-film trough and a back-surface glass trough for comparison, see Table 1.

[1] The numbers provided here include only plants larger than 9 MW and listed as operating, in commissioning, or under construction.

Table 1. Commercial Parabolic Troughs Examined in this Study

Property	SkyTrough	Ultimate Trough
Manufacturer	SkyFuel (USA)	FLABEG (Germany)
Reflector type	ReflecTech PLUS polymer film	4-mm glass
Aperture (m)	6.0	7.51
Module length (m)	13.9	24.5
Solar collector assembly (SCA) length (m)	115	247
Modules per SCA	8	10
SCA aperture area (m^2)	656	1,689
Frame design	Space frame	Torque box
Primary frame material	aluminum	Steel

Figure 3 shows a module and a solar collector assembly (SCA) of the SkyTrough to highlight how a module is the smallest complete element of an SCA. Support pylons exist between modules, which are strung together to form an SCA. The SkyTrough uses 8 modules per SCA while the Ultimate Trough uses 10 modules per SCA.

Figure 3. SkyTrough Module (left) and SCA (right). A module represents the smallest unit of a parabolic trough solar field. An SCA is a series of modules controlled by a single drive system.

(Photos, left, by Parthiv Kurup, NREL; right, from SkyFuel)

3 Approach and Methodology

3.1 Key Assumptions and Limitations

The aim for the SkyTrough and Ultimate Trough bottom-up costing exercise has been to create a representative case for both designs at a commercial scale. As such, there have been many key assumptions needed for this initial bottom-up cost modeling and investigation. The most important of these assumptions are discussed below.

Representative designs for the SkyTrough and Ultimate Trough have been created. The representative designs created in this investigation assume that all the individual trough modules[2] and SCAs in the solar field (SF) are the same. Industrial experience with commercial projects has shown that when a project-based SF is designed, the SF must take into account site-specific considerations such as land and soil conditions as well as wind loading. Inclusion of these factors leads to changes in the collector structures across the SF. For example, reinforced collectors can be used along the periphery where higher strength and torsional rigidity are required to offset the wind loading. However, the NREL analysis examined only the standard internal-field module for each design.

A plant of 100 MW_e with six hours of TES was selected as the representative plant size. This is consistent with prior analyses (C. Turchi 2010) and representative of current projects. The approximate SF aperture area is 1 million square meters and would be dependent on the assumed solar multiple, location and associated Direct Normal Irradiance (DNI) resource. The exact SF size is not critical, but it was necessary to specify a size that could be used for the production volume calculation within the design for manufacturing and assembly (DFMA) software. The scope of this analysis relative to the cost categories within SAM is outlined in Table 2. Notably, the header piping and the HTF that are utilized in the SF were excluded from the analysis; the receiver cost is included within the SF subsystem. The SkyTrough SF has been estimated using receiver tubes that would contain synthetic oil as the HTF. The cost of the Ultimate Trough design has been estimated using receiver tubes that are suitable for use with molten salt as the HTF. While this impacts the selected diameter of the receiver tube, the developer indicates that the structural supports of the Ultimate Trough are largely the same for oil- or salt-HTF applications.

[2] Trough modules are also referred to as solar collector elements (SCEs). The term SCE is more common in the international market.

Table 2. Parabolic Trough Direct Capital Cost Categories within SAM (C. Turchi 2010).

SAM Direct Capital Cost Categories	Source
Site Improvements	(C. Turchi 2010)*
Solar Field, which includes: • Solar collector mirrors • Solar collector receiver tubes and fittings • Solar collector frame • Solar collector assembly misc. components • Foundations and support structures • Instruments and controls • Electrical • Installation labor • Assembly infrastructure: temporary building, jigs, crane rental, etc.	This study
HTF System, which includes: • Freeze protection system • Ullage system • HTF pumps • Expansion systems • Solar field header piping, insulation, and fittings • Power block piping, insulation, and fittings • Foundations and support structures • Fluid	(C. Turchi 2010)*
Storage (components of the subsystems listed in (C. Turchi 2010)	(C. Turchi 2010)*
Fossil Backup	(C. Turchi 2010)*
Power Plant	(C. Turchi 2010)*
Balance of Plant	(C. Turchi 2010)*

* These costs will be updated to 2015 values in SAM by indexing the 2010 study values for inflation.

The following sections provide the estimates and breakdowns for the installed cost per square meter of aperture area. Project-specific factors that may influence pricing such as project financing, markups, and significant transportation costs have been excluded from the analysis. This analysis estimates the cost of potential manufacturing, assembly, and then installation of the SF for commercial scales of the SkyTrough and Ultimate Trough at approximately 1 million square meters. Although both designs are commercially available and have been deployed, neither has reached commercial deployment at that scale.

It was assumed that tooling investments would not be needed for standard manufactured components (e.g., angle brackets), and these costs were only included where specific geometries or special parts were needed (e.g., aluminum extrusions). Where necessary, investment in tooling has been calculated and shown as a separate line item. For assembly activities, an Arizona merit-shop labor rate of $15/hr was used (C. Turchi 2010).

3.2 Method for Investigation

The method used to analyze the SkyTrough and the Ultimate Trough is shown in Figure 4.As noted in Figure 4, the geometry of some parts associated with the SkyTrough required custom CAD models (e.g., Figure 5) that were not necessary for the Ultimate Trough analysis.

Figure 4. Method for determining the installed cost for the SkyTrough and Ultimate Trough designs.

3.3 Bill of Materials (BOM) Development

The BOM for the SkyTrough and Ultimate Trough designs is critical and underpins the bottom-up cost analysis. The NREL BOM for each reference case consisted of the total number of components and subassemblies that would be required to build the modules and then the SCAs, which would then constitute the assemblies needed for the specified SF size. For a project scenario, the BOM would include the complete set of parts, instrumentation, materials, and pre-assembled parts that would be used by the Engineering Procurement & Construction (EPC) contractor to assemble the SF.

As much as possible, the SkyTrough and Ultimate Trough BOMs were created using publicly available information such as published reports (Ruegamer et al. 2014). Other data sources included patent documents, site visits, engineering calculations, and discussions with industry contacts (Gee et al. 2014; Niemeyer 2015). The purpose of this approach was to make an independent validation—without having to be given access to proprietary design documents by the technology developers. An understanding of the individual components, estimated dimensions, materials used, and the quantity involved (e.g., the number of reflective panels) is the foundation for the manufacturing, assembly, and installation analysis.

3.4 Design for Manufacture and Assembly

A key tool in the analysis has been a suite of software tools called Design for Manufacture and Assembly (DFMA), from Boothroyd Dewhurst. This tool was used in a previous NREL analysis from which the installed cost of a state-of-the-art commercial heliostat design was derived (C. S. Turchi et al. 2015).

The DFMA software package is used industry-wide and has two parts: Design for Manufacture (DFM) and Design for Assembly (DFA). For this analysis, the version of the DFM software was 2.4.0.18 and for the DFA software it was 10.0.1.103 (Boothroyd Dewhurst Inc. 2015a). The DFMA tool has detailed databases and allows the knowledgeable user to calculate a primary manufacturing cost for each component and then assemble it within the overall product/assembly. DFM was used for the majority of the components within the BOMs to model the trough as if it were to be manufactured in commercial quantities. As such the material, manufacturing processes (e.g. stock processes), key dimensions, and machining steps were estimated. Note that every component that could be directly manufactured in a commercial-scale manufacturing and fabrication shop was modeled because such specialist components such as receiver tubes or mirror panels were beyond the DFMA capabilities.

DFM allows the user to produce a detailed “should-cost” number that is based on what a component should cost from the manufacturer; the number is based on material, process steps, machine setup time, and tooling if needed. Tooling investment is calculated for special processes such as stamping and also takes into account tool wear and life based on the life volume of the parts needed for the BOM. DFA was then used to assemble (e.g., weld) the components together into subassemblies and to cost the full assembled SCA based on parameters such as the number and type of cranes needed and assembly labor rate. DFMA was used for the collector frame structure but not used for the installation estimates for the foundations.

For the next step, DFM has the ability to accept Computer Aided Design (CAD) models as inputs to allow the part to be modeled for manufacturing. For the SkyTrough BOM, significant CAD models were needed due to the complexity of the parts—especially for certain components such as the strut connectors. An example CAD model of a SkyTrough Space Frame connector can be seen in Figure 5.

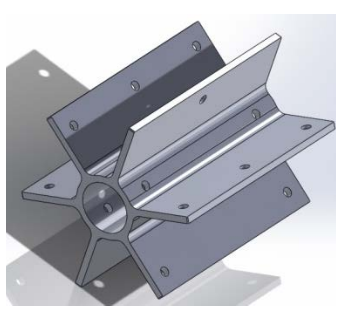

Figure 5. CAD model of a spaceframe connector for the SkyTrough used as input into DFM

(Illustration by Parthiv Kurup, NREL)

A key feature of the DFMA tool was the built-in ability to change the life volume of the manufactured parts to compare the effects of small numbers of production versus commercial-scale manufacturing. For example, increasing production volume from 15 to 15,000 for the connector shown in Figure 5 caused the final manufactured part cost to drop from approximately $1000/part (for 15 produced, intersecting red lines in Figure 6) to approximately $50/part (for 15,000 produced). This difference includes the tooling investment in the total part cost.

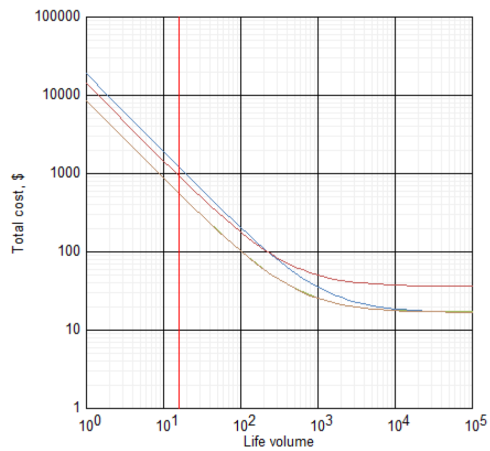

Figure 6. Effects of manufacturing the SkyTrough connector at a variety of production scales

(Illustration by Parthiv Kurup, NREL)

3.5 Interaction with Trough Developers

To build the bottom-up costing of the selected SkyFuel and FLABEG trough designs, interaction with the CSP industry was needed. Both companies were very cooperative with NREL's analysts, and data and figures internally generated at NREL have been shared with the respective developers.

For specific key components such as the receiver tubes, reflective mirror panels, and drive systems, price quotes were received from the component manufacturer or installer. The specific details of the discussions and estimates provided from the industry have been excluded from this report to protect the sensitive information provided. It must be stated that the cost estimates from suppliers and manufacturers used in this investigation are based on large-scale commercial application of the technology. To determine the current market commodity prices of the steel and aluminum (as raw materials and as manufactured parts), price indices for the commodities were created and utilized in the DFMA cost databases.

4 SkyTrough Design Analysis

4.1 Design description

SkyFuel's SkyTrough parabolic collector uses the reflective polymer thin-film ReflecTech PLUS (DiGrazia, Gee, and Jorgensen 2009; Mason and Reitze 2014; SkyFuel Inc. 2011). ReflecTech PLUS is a highly reflective material that is adhesively bonded to an aluminum substrate. The manufacturer reports excellent abrasion resistance and durability due to a protective hardcoat and extensive weathering tests (http://www.reflectechsolar.com/technical.html). The SkyTrough is an advanced collector design that is in use at Enel Green Power's Stillwater Geothermal/Solar Hybrid plant in Nevada, the Medicine Hat Integrated Solar Combined Cycle (ISCC) in Canada, and the Panoche Desalination plant in California (Enel Green Power and SkyFuel Inc. 2014; SkyFuel Inc. 2015; WaterFx 2015). At the time of this writing, the SkyTrough is yet to be deployed in a large-scale CSP plant.

Figure 7. Front and rear of a SkyTrough module; eight modules collectively form an SCA.

(Photos by Parthiv Kurup, NREL)

As can be seen from Figure 7, the SkyTrough comprises an aluminum spaceframe (struts and connectors) and ReflecTech PLUS panels, which can slide into extruded ribs that hold the trough shape and the optical performance of the trough (Gee et al. 2014; Hawkins, Farr, and Gee 2014). The majority of the spaceframe is made up of Al 6051 structural tubes. The design has been developed to allow for ease of construction—without need for assembly jigs—and can be assembled as a structure mainly through riveting.

The NREL SkyTrough BOM and analysis utilized an 80-mm receiver tube (which uses synthetic oil as the HTF) per the current SkyTrough design. The analysis in the following section has been undertaken for 1500 SCAs. The necessary regular pylons and drive pylons have been included; however, the header piping and HTF volumes have been excluded. These components are accounted for under SAM's HTF System cost category (see Table 2).

4.2 Subsystem Categories

The main subsystem categories for the NREL SkyTrough BOM and analysis can be seen in Figure 8. The key subsystems for the SkyTrough module and SCA analysis were the receivers, receiver supports, mirror panels, parabolic ribs, space frame, torque plates, drives and control, drive pylon and regular pylons, and the foundations.

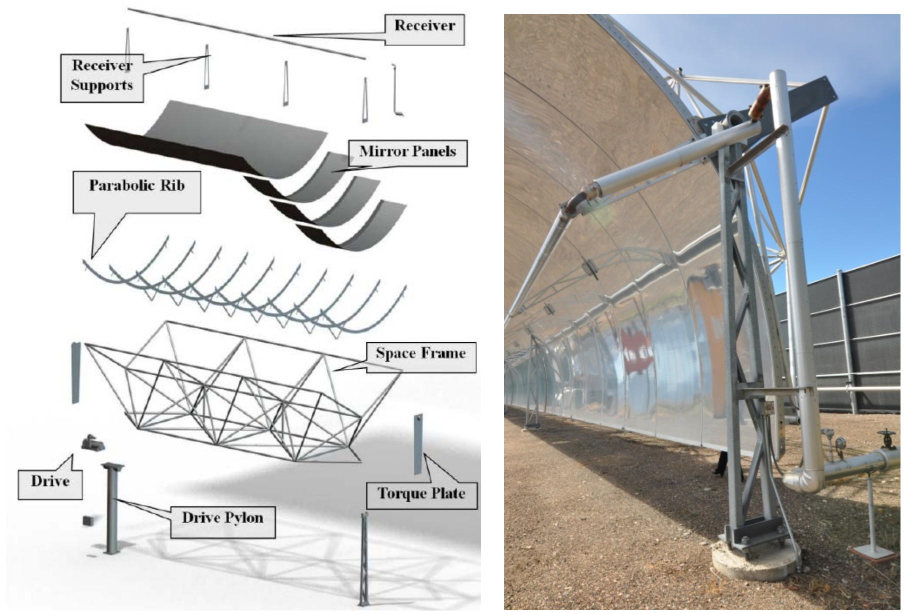

Figure 8. Main components of the SkyTrough module and picture of regular pylon

(Illustration from SkyFuel; photo by Parthiv Kurup, NREL)

Within each subsystem NREL applied significant effort to determine the current components and dimensions. Costs have been estimated using manufacturing analysis for the subsystems (including the manufacture of the drive and nondrive support pylons). Construction activities were also included to create cost estimates of digging and adding the foundations for 1500 SCAs.

As ReflecTech PLUS and the receiver tubes were costed by the manufacturers based on the scale of the project, they also provided specific manufacturing costs. For example, costs were provided for 36,000 80-mm OD x 4.06-m long receiver tubes and 108,000 ReflecTech PLUS Sheets (each at approximately 6.7 m x 1.5 m (22 ft x 5 ft).

Each subsystem was broken down into the specific components that would make up a module and an SCA; then the result was scaled to 1500 SCAs. From the component level, the BOM and then the manufacturing, assembly, and installation analysis per SCA followed. For example, the NREL analysis found that the space frame was made up of at least eight different spaceframe connectors in a module. Depending on the type, the number of specific connectors per SCA varied. While it was clear that the space frame was made up of extruded aluminum tubes with pressed ends, there were many varieties of tube dimension and thickness within the frame (Hawkins, Farr, and Gee 2014). The Helac L-30 380 Helical Rotary drive system utilized in the analysis was the standard 499-kg (1100-lb) drive, which is capable of 180° of rotation (Helac Corporation 2015a; Helac Corporation 2015b). It was understood that a modified drive with increased rotation (e.g., up to 270°) might be preferred; however, such a drive was stated to be only marginally more expensive to manufacture. Figure 9 shows different components (e.g., spaceframe, connectors, and torque plates) and subsystems used for the analysis.

Figure 9. Different components in the SkyTrough module and SCA from the test sites at Arvada, Colorado and the Stillwater plant in Fallon, Nevada

(Left and right photos by Guangdong Zhu, NREL; center photo by Parthiv Kurup, NREL)

The NREL analysis found that nearly 2400 individual parts were needed for each regular SCA. Details from the SkyTrough analysis have been summarized into Table 3.

Table 3. Summary of the Individual Components per Subassembly for the NREL SkyTrough Analysis.

Each SkyTrough SCA contains one or more of the listed subassemblies. Due to simplifications in NREL's representative model, the NREL parts count may not match the actual fabrication parts total.

Subassembly	Individual Component types per Subassembly	Details
Torque Plates	4	Galvanized steel structures
Pylons (Regular and Drive)	16	Galvanized steel structures
Foundations	9	Steel reinforced concrete. Eight Regular pylons and one drive pylon.
Drive and Controls	1	Helac L-30 360 drives. 1100 lb
Parabolic Ribs	4	Pressed/stamped Al ribs. Extruded guide rails to position mirror panels
Mirror Panels	4	ReflecTech PLUS bonded onto 0.05" Al substrate (DiGrazia, Gee, and Jorgensen 2009)
Spaceframe	29	Extruded Al tubes and extruded connectors. Riveted fastening
Receivers	24	80-mm OD receiver tubes
Receiver Supports	5	Galvanized steel structures

4.3 Installed Cost ($\$/m^2$) for 1500 SCAs

The NREL analysis on the manufacturing, assembly, installation equipment, and construction activities assumed a production volume of 1500 SCAs, which is representative of a 100-MW_e plant with TES. For an aperture width of 6 m with a net aperture area of 656 m^2, it is estimated that the overall installed cost for the SkyTrough 115-m design is approximately \$170/m^2. This figure includes a manufacturing investment to purchase tooling for specific SF components. By design, specific assembly tooling and jigs are unnecessary—the SkyTrough has been designed to be assembled onsite without special equipment. The \$270,000 manufacturing investment is included for subsystems such as the stamping machine for the parabolic ribs and the specifically shaped casting dies needed for the aluminum extrusions (e.g., the connectors in the spaceframe). When the manufacturing tooling investment is amortized over 1500 SCAs, it adds less than \$1/m^2 to the installed cost. The breakdown of the subsystems as a proportion of the total installed cost is shown in Figure 10. This cost includes the SF assembly into the subsystems.

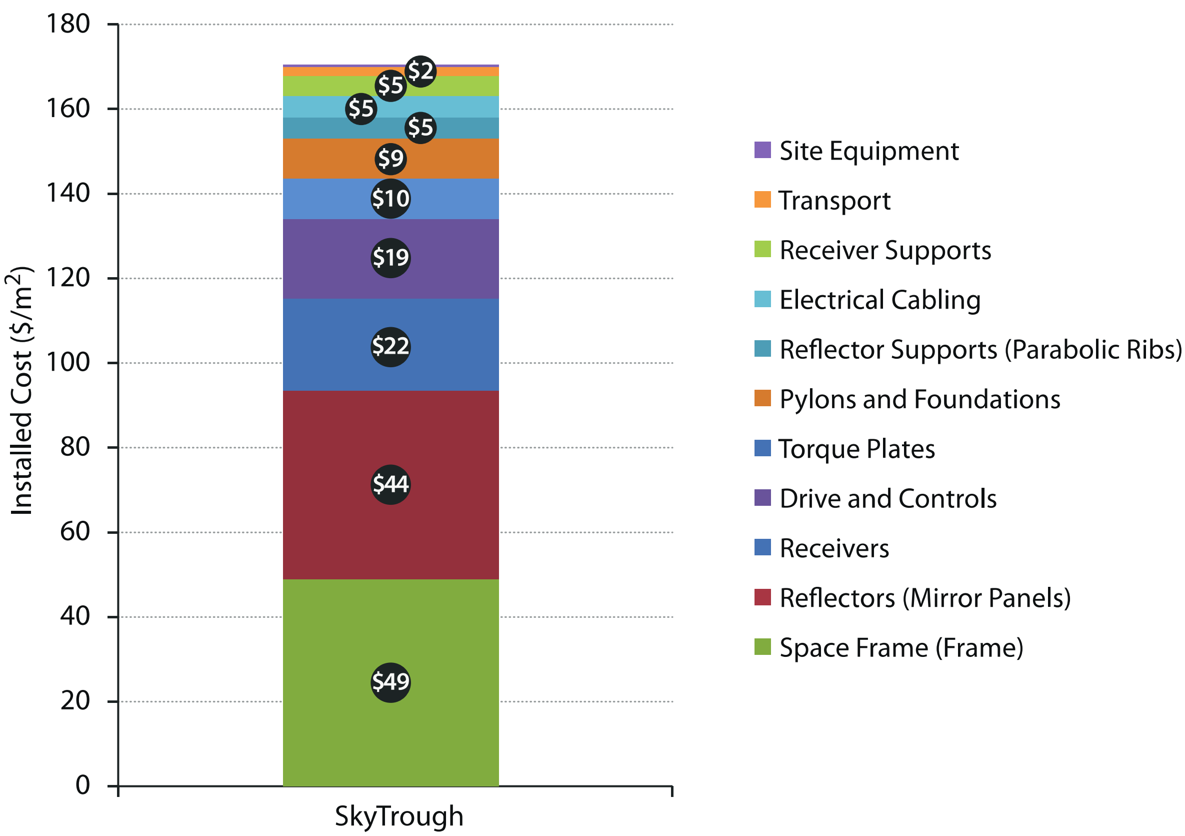

Figure 10. Installed cost for the SkyTrough assuming 1500 SCAs. Total installed cost is estimated at \$170/m^2.

(Illustration by Al Hicks, NREL)

As can be seen in the chart, it was found that the space frame and reflector panels each contributed a little less than 30% of the installed cost. The next largest cost contributors are the receivers (13%) and the drive and control system (11%).

5 Ultimate Trough Design Analysis

5.1 Design Description

The FLABEG FE Ultimate Trough was the selected parabolic trough design that used more traditional glass mirrors as the reflective surface (“Ultimate Trough Technology,” n.d.). The 7.5-m aperture Ultimate Trough has been designed to use either molten salt or synthetic oil as the HTF. Depending on the chosen HTF, the Ultimate Trough can utilize either 70-mm or 90-mm OD receiver tubes (Ruegamer et al. 2014; Zhu and Neises 2015). Discussions with the developer have highlighted that the Ultimate Trough was developed for larger RP5 mirrors (a FLABEG product) but can also utilize the more commonly produced and slightly smaller RP6 mirrors (FLABEG FE 2014; “Ultimate Trough Technology,” n.d.).

The Ultimate Trough was collectively developed by FLABEG GmbH (now FLABEG FE); Schlaich Bergermann und Partner, Sonne GmbH (SBP); and the Fraunhofer Institute for Material Flow and Logistics. Support was provided by the German government and the German Aerospace Center (DLR) (K. Riffelmann et al. 2014; Weinrebe, Balz, and Schiel 2013). The Ultimate Trough collector that uses synthetic oil as the HTF has been deployed and operating since January 2013 as a demonstration loop. The collector consists of two SCAs (20 modules) at Harper Lake, California, and has a net aperture area of 3,378m^2 (K. Riffelmann et al. 2014). Performance of this loop has been validated by NREL researchers (Zhu and Neises 2015). An Ultimate Trough SCA is composed of ten modules; a full loop typically consists of four SCAs. The larger size aperture and SCA shows promise for reduced cost (per m^2) for receivers and drive systems.

Parts of the test loop at Harper Lake are shown in Figure 11. As of September 2015, there has yet to be a commercial deployment of the Ultimate Trough or a fully developed test loop using molten salt.

Figure 11. Ultimate Trough test loop and close-up of an SCA at Harper Lake, California

Photos from FLABEG

The Ultimate Trough is an advancement of one of the most commercially used CSP parabolic troughs—the EuroTrough. The Ultimate Trough is estimated to save 20%-25% on installed cost compared to a EuroTrough SF of approximately the same thermal output (Schweitzer et al.

2014). The design and scale of the Ultimate Trough is targeted for large-scale power generation, e.g., 100-400 MW_e (K.-J. Riffelmann, Graf, and Nava 2011).

The design philosophy for the Ultimate Trough was to nearly double the size of an SCA and significantly decrease the parts and components versus the EuroTrough. Relative to the EuroTrough's 12-m long modules, the Ultimate Trough has 24.5-m modules (FLABEG FE 2014). The net aperture area for an Ultimate Trough SCA is 1,689 m^2 (Zhu and Neises 2015) compared to the EuroTrough's 817.5 m^2. The aperture width is 7.51 m versus 5.77 m, respectively (Weinrebe, Balz, and Schiel 2013). The larger SCA decreases the count of SCA-specific components like the drive units, sensors, controls, pylon foundations, and loop piping. This decrease leads to an overall SF component decrease of nearly 50%. Table 4 shows the SF comparisons between the EuroTrough and the Ultimate Trough for a 50-MW_e site with 8 hours of TES and for a 250-MW_e site without TES.

Table 4. Comparison of the EuroTrough and Ultimate Trough SFs for Two Plant Configurations

	50-MWe plant with 8 hours storage and Solar Multiple of 2.0 (e.g., Andasol 1) (FLABEG FE 2014; SBP 2013)		**250-MWe plant without storage** (Schiel 2011)	
Design Parameter	*EuroTrough*	*Ultimate Trough*	*EuroTrough*	*Ultimate Trough*
Solar Field Area (m^2)	510,120	466,731	1,239,330	1,141,629
Loops	156	68	379	169
SCAs	608	272	1516	676
Drives, Sensors and Controls	608	272	1,516	676
Pylon Foundations	7800	2992	18,950	7,436
Swivel Joints	1248	544	3,032	1,352
Crossover Pipes	156	68	379	169

As can be seen in the table, the reduction in parts count for the Ultimate Trough offers the potential for significant cost savings versus the smaller EuroTrough. In addition to the larger design, the use of the Ultimate Trough with a molten-salt HTF offers significant opportunity for cost saving in parabolic trough plants.

The analysis in the following section has been undertaken for 700 Ultimate Trough SCAs (175 loops). The Ultimate Trough uses hot dipped galvanized steel (e.g. tubular steel sections) for the majority of its subsystems. Regular pylons and drive pylons have been included. The HTF system piping and HTF volume have been excluded, as before with the SkyTrough.

5.2 Subsystem Categories

The main subsystem categories for the NREL Ultimate Trough BOM and assembly analysis were the receivers, receiver supports, mirror panels, cantilever arms, torque box, end plates, drives and control, pylons (regular, drive and crossover), and the pylon foundations. The analysis assumed that the Ultimate Trough configuration employed a molten-salt HTF. Though NREL had concerns that molten salt in the receiver tubes would increase the load placed on the receiver supports and perhaps lead to significant changes in the design relative to the oil-HTF version, FLABEG assured NREL that there is little structural change of the overall design of the Ultimate Trough for this conversion. The main difference for the molten-salt Ultimate Trough is that six receiver tubes are needed per module instead of the five used for the oil-HTF version. The NREL analysis used 70-mm OD x 4.06-m long receivers and accounted for the increased numbers of receivers needed. Likewise, the Ultimate Trough design has been designed to accept both RP5 and RP6 mirrors so the RP6 mirrors have been assumed here. This assumption led to a need for more mirrors. The crossover pylons have been included based on one crossover pylon per loop.

Within each subsystem, NREL applied significant effort to determine the dimensions of the components. Costs have been estimated using manufacturing analysis for the subsystems (including the manufacture of drive and nondrive pylons). Construction activities were also included to create cost estimates of adding the foundations for 700 SCAs. Figure 12 shows pictures from the Ultimate Trough test loop at Harper Lake, California.

Figure 12. Pictures of the Ultimate Trough oil test loop at Harper Lake, California

(Photos from FLABEG)

An indication of the how the Ultimate Trough has been developed for large commercial-sized SFs is apparent from the level of automation and the number of assembly jigs needed to build the SCAs. Even for a relatively small SF, at least one set of box, module (SCE), and mirror jigs are needed (see Figure 13). Assembly can be conducted outside, so an assembly building is not required.

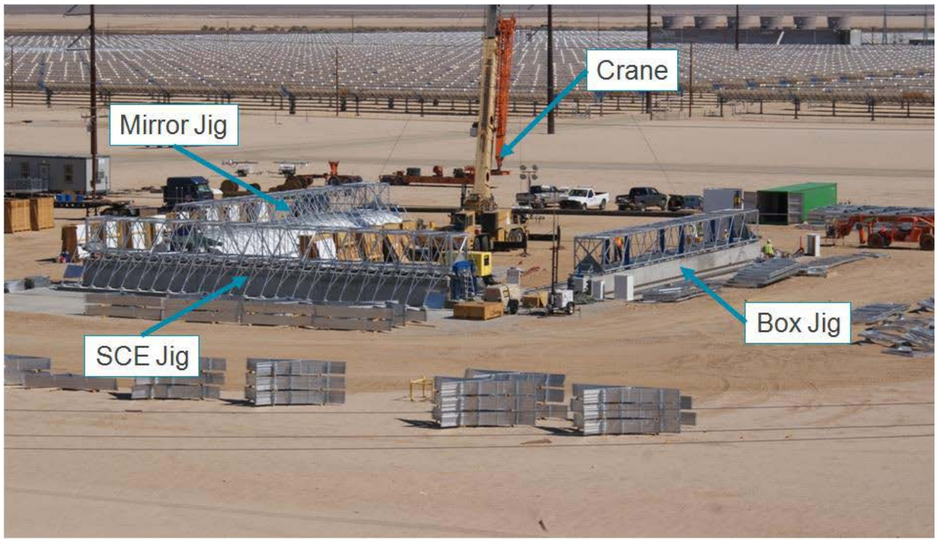

Figure 13. Box, module (aka SCE), and mirror jigs needed for the assembly of the Ultimate Trough SCA test loop

(Photo from FLABEG)

The Ultimate Trough has been designed for large commercial-scale deployment, and ways to increase the production rate of the finished SCAs have been considered throughout the build and assembly process. Power tool-based lock bolts (for attaching the cantilever arms to the torque box), semi-automated mechanical clinging machines for the torque box, and an automated gluing machine for attaching the mirror pads to the cantilevers have all been utilized. It has been estimated that an Ultimate Trough SF of 1,002,099 m^2 (146 loops) would require two parallel assembly lines with overhead cranes occupying approximately 116 m x 63 m ("Ultimate Trough Technology," n.d.; Schweitzer et al. 2014). For the NREL analysis, the main subsystems used for the 700 SCAs are listed in Table 5.

Table 5. Main Subsystems for the Ultimate Trough Analysis

Each Ultimate Trough SCA contains one or more of the listed subassemblies. Due to simplifications in NREL's representative model, the NREL parts count may not match the actual fabrication parts total.

Subassembly	Individual Component Types per Subassembly	Details
Cantilever Arms	11	Galvanized steel structures
Torque Box	9	Galvanized steel structures
End Plates	9	Galvanized steel structures
Pylons (drive, regular, and crossover)	29	Galvanized steel structures
Drive, controls, and sensors	4	Hawe Hydraulics
Mirror Panels	1	RP5 Mirrors
Receivers	1	70-mm OD receiver tubes with advanced materials are needed to utilize the high-temperature molten salt
Receiver Supports	8	Galvanized steel structures

5.3 Installed Cost ($/m^2$) for 700 SCAs

NREL estimated that the overall installed cost for the Ultimate Trough (which would use molten salt) as $178/m^2. This assumed the case of an SF with 700 SCAs (i.e., an aperture area of 1,182,300 m^2).

The Ultimate Trough analysis found that both manufacturing and specialist assembly tooling investments would be needed. The manufacturing tooling investment was estimated to be approximately $482,000. This is a relatively small value and adds less than $1/m^2 to the overall installed cost. However, based on the commercial scale of the SF (i.e., 175 loops) it is assumed that at least two parallel assembly lines would be needed—each with specific jigs for the torque boxes, modules, and mirror attachment. The assembly investment has been estimated at $11.6 million. Overall, this cost adds about $10/m^2 to the total installed cost and has been distributed among the relevant subsystems—for example, the cantilever arms, torque box, and mirrors. The breakdown of the subsystems as a proportion of the total installed cost is shown in Figure 14.

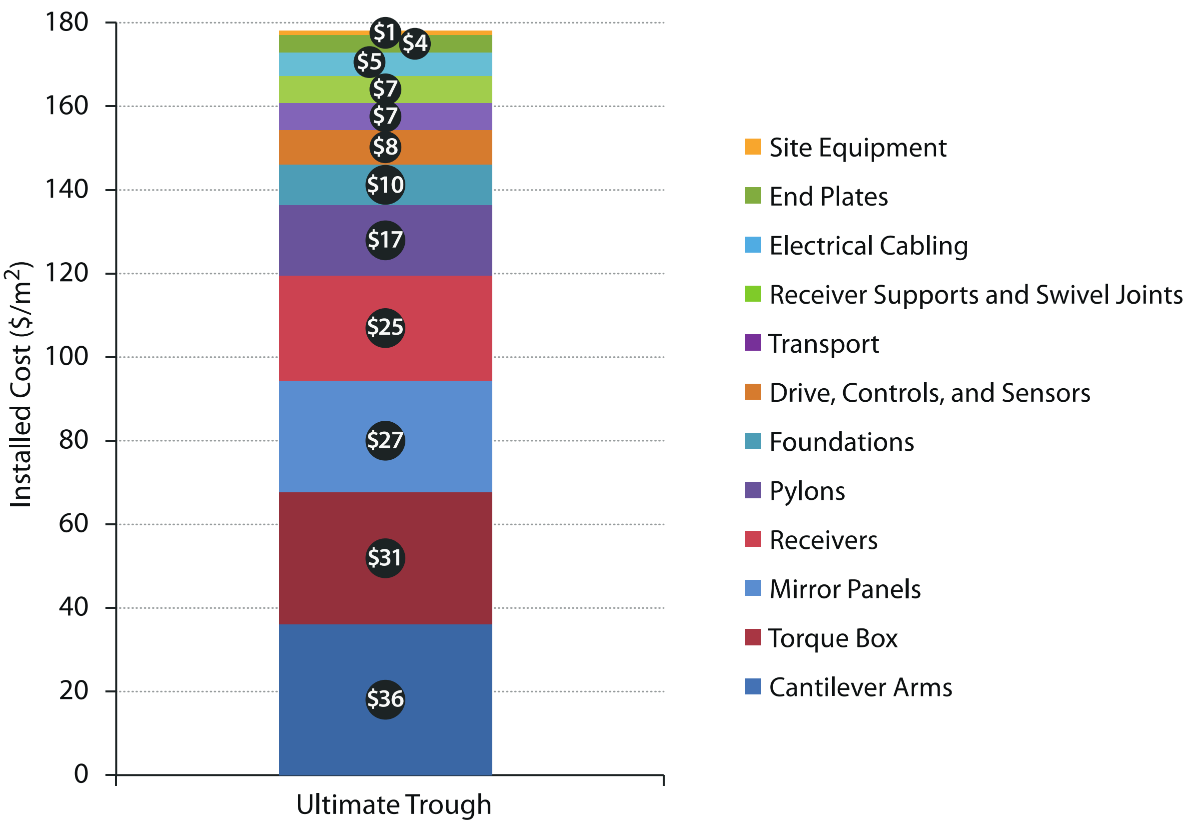

Figure 14. Installed cost for the Ultimate Trough assuming 700 SCAs. Total installed cost is estimated at $178/m^2.

(Illustration by Al Hicks, NREL)

6 Updates to SAM defaults

6.1 Updates to SAM's Parabolic Trough Models

Based on the preceding analysis, the default cost values in SAM's parabolic trough models are updated with the values shown in Table 6. The SkyTrough is used as the new default solar collector based on the larger amount of supporting information in the current study. In addition to the updated solar field cost number, most other cost inputs are indexed from 2012 to 2015 using the Chemical Engineering Plant Cost Index (CEPCI). The year 2012 is the baseline in this update because NREL last surveyed CSP developers to update SAM cost inputs in that year. NREL's power tower cost study (C. S. Turchi and Heath 2013) also used 2012 dollars. Accordingly, the present update indexes many values from 2012 to 2015, with some exceptions that are indicated below.

The CEPCI includes a composite index and ten individual indices representing cost categories such as "heat exchangers & tanks," and "construction labor." NREL's plant models use the specific CEPCI index that is most suited for each cost category as described in the spreadsheet-based plant models for the parabolic trough and molten-salt power tower are available at the SAM website at https://sam.nrel.gov/cost.

Table 6. SAM Cost Updates for the Parabolic Trough Models.

The solar field value is updated by the analysis described here.
The other values are updated to 2015$ using the CEPCI
("Economic Indicators: Chemical Engineering Plant Cost Index [CEPCI]" 2015).

SAM Cost Category	Value in SAM 2015-06-30	New Value	Comments
Site Improvements ($\$/m^2$)	30	30	
Solar Field ($\$/m^2$)	270	170	SkyTrough used as default
HTF System ($\$/m^2$)	80	70	
Storage ($\$/kWh_{th}$)	80	75	
Fossil Backup ($\$/kW_e$)	-	-	Not used
Power Plant ($\$/kW_e$)	830	1150	Switched to dry-cooled power block
Balance of Plant ($\$/kW_e$)	110	120	BOP is defined as the steam generation system
O&M fixed cost by capacity ($\$/kW_e$-yr)	65	66	
SAM Levelized PPA Price (real $/kWh)	14.9	13.9	From default case with SkyTrough as solar collector. Includes 30% ITC.

The site improvements and O&M fixed cost categories are dominated by labor costs. Construction and engineering labor cost indices have changed very little between 2012 and 2015 and that trend is reflected in the updates.

The update for the thermal energy storage system ("Storage" in SAM) was estimated by applying the CEPCI adjustment to the tanks, piping, and hardware cost components and using a new supplier quote for the cost of the solar salt. The salt cost estimate increased only marginally from the prior value—from $1080 to $1100 per metric ton for salt delivered to southern California.

The HTF System was updated by applying the CEPCI adjustment to the tanks, piping, and hardware cost components and by using the producer price index for aromatic chemicals (PPI WPU06140197) to adjust the cost estimate for the synthetic oil HTF from 2012 to 2015. Oil prices are relatively volatile compared to the other cost components. In this case the annual PPI value changed from 443.0 to 280.7 from 2012 to 2015, which resulted in a large decrease in the cost index of the HTF. The index for "pipe, valves, and fittings," also fell over this period, although not as dramatically. Including fluid and hardware, the decrease in the HTF system cost was about 12%.

Power block updates reflect two significant changes: a switch to dry cooling and indexing to the 2015 cost year. The change to an air-cooled plant impacts cycle efficiency and cost. The rated cycle conversion efficiency is changed from 0.3774 to 0.356 with a design-point ambient dry-bulb temperature of 42°C as per (C. Turchi 2010, Turchi et al. 2010). The number of cooling system part-load levels is increased from 2 to 8 reflecting the greater control possible with multiple air-cooled condenser fans. Because a dry-cooled trough plant was not included in the 2012 cost survey, the cost values are indexed from 2009 (C. Turchi 2010) to 2015.

The resulting new cost numbers in Table 6 reflect innovation and improvements in solar collector technology during the past several years—while the HTF, TES, and power block subsystems have been largely unchanged and have costs affected only by market and inflationary factors. Further innovations such as the deployment of molten-salt HTFs are required to drive down the cost of these other plant systems.

The Physical Trough Model in SAM 2015-06-30 was used to examine the impact of the revised cost values on LCOE, which is redefined in SAM 2015 as the levelized power purchase agreement (PPA) price (see SAM help menu for definitions of the various cost terms). The SAM default case was first adjusted to select the SkyTrough as the solar collector and the power block settings were changed to air cooling. Direct Capital Costs were then changed as indicated in Table 6. This adjustment led to a change in the estimated real levelized PPA price from 14.9 ¢/kWh to 13.9 ¢/kWh. Note that the SAM default case includes a 30% investment tax credit (ITC).

6.2 Other Updates to SAM

In addition to the updates for SAM's parabolic trough models, other CSP models were updated to bring the values to a consistent 2015 cost year. The additional changes are outlined in Table 7. No changes were made to the CSP Dish-Stirling model.

Table 7. Additional SAM Default Value Updates for the 2015 Cost Year.

SAM Input	Value in SAM 2015-06-30	New Value	Comments/Basis
Molten Salt Power Tower Model			
Site improvements ($/m^2)	15	16	Indexed for 2012 to 2015
Heliostat Field ($/m^2)	170	170	Indexed for 2013 to 2015
Balance of Plant ($/kW$_e$)	350	340	Indexed for 2012 to 2015
Power Block ($/kW$_e$)	1200	1190	Indexed for 2012 to 2015
Storage ($/kWh$_t$)	27	26	Indexed for 2012 to 2015
O&M fixed cost by capacity ($/kW$_e$-yr)	65	66	Indexed for 2012 to 2015
Direct Steam Power Tower Model			
Site improvements ($/m^2)	15	16	Indexed for 2012 to 2015
Heliostat Field ($/m^2)	170	170	Indexed for 2012 to 2015
Balance of Plant ($/kW$_e$)	0	0	no separate steam generation system
Power Block ($/kW$_e$)	1200	1190	Indexed for 2012 to 2015
O&M fixed cost by capacity ($/kW$_e$-yr)	50	50	Indexed for 2012 to 2015
Molten Salt Linear Fresnel Model			
Site improvements ($/m^2)	20	20	Indexed for 2012 to 2015
Solar Field ($/m^2)	350	170	Set to match the parabolic trough solar field cost as an upper bound for a Linear Fresnel system.
HTF System ($/m^2)	50	47	Indexed for 2012 to 2015
Balance of Plant ($/kW$_e$)	0	340	Matching molten-salt power tower
Power Block ($/kW$_e$)	880	1190	Matching dry-cooled power tower
Storage ($/kWh$_t$)	Missing	32	Scaled from molten-salt power tower value by the ratio of ΔTs
Contingency	10%	7%	Consistent with other CSP models
EPC and Owner Cost	15%	11%	Consistent with other CSP models
O&M fixed cost by capacity ($/kW$_e$-yr)	50	66	Matching molten-salt power tower
Direct Steam Linear Fresnel Model			
Site improvements ($/m^2)	20	20	Indexed for 2012 to 2015
Solar Field ($/m^2)	180	170	Set to match the parabolic trough solar field cost as an upper bound for a Linear Fresnel system.
HTF System ($/m^2)	35	33	Indexed for 2012 to 2015
Balance of Plant ($/kW$_e$)	0	0	no separate steam generation system
Power Block ($/kW$_e$)	940	1190	Matching dry-cooled power tower
O&M fixed cost by capacity ($/kW$_e$-yr)	50	50	Indexed for 2012 to 2015
CSP Generic Model			
Site improvements ($/m^2)	15	16	Matching power tower
Solar Field ($/m^2)	260	260	Matching power tower when tower/receiver system is included
Storage ($/kWh$_t$)	27	26	Matching molten-salt power tower
Power Block ($/kW$_e$)	1550	1530	Matching molten-salt power tower when BOP included
O&M fixed cost by capacity ($/kW$_e$-yr)	65	66	Matching molten-salt power tower

Molten-Salt and Direct-Steam Power Tower

Changes to the molten-salt power tower model are all due to indexing. Most of the changes adjust costs given in (C. S. Turchi and Heath 2013) to 2015. The exception is the heliostat cost, which is updated from 2013 see (C. S. Turchi et al. 2015) to 2015. *It is interesting, but merely coincidental, that the 2015 heliostat field cost and the 2015 parabolic trough solar field costs are both $\$170/m^2$.*

Molten-Salt and Direct-Steam Linear Fresnel

NREL has not completed a detailed analysis of linear Fresnel solar field costs, nor are there detailed Fresnel system costs in the open literature. Therefore, the solar field cost input for the Fresnel models was set equal to the parabolic trough solar field cost. Because the promise of linear Fresnel is a lower capital cost versus troughs, this is assumed to be an upper bound for a fully developed linear Fresnel design.

The power cycle for each Fresnel model is switched to air cooling to be consistent with the other CSP models. The air-cooled power block costs are assumed to match those for the molten-salt power tower model. In addition to increasing the capital cost per kilowatt of capacity, switching to air cooling necessitates a change in SAM's rated cycle conversion efficiency. The cycle efficiency at design is adjusted to be consistent with the trough and power tower cases as shown in Table 8.

Table 8. Power Cycle Gross Efficiency Default Values.

SAM model(s)	SAM rated cycle conversion efficiency	Source
Physical and Empirical Trough	0.356 at 391 °C*	Air-cooled plant, (C. Turchi 2010).
Direct-Steam Linear Fresnel	0.371 at 440 °C	Interpolated
Molten-Salt Linear Fresnel	0.397 at 525 °C	Interpolated
Direct-Steam Power Tower	0.404 at 550 °C	Interpolated
Molten-Salt Power Tower	0.412 at 574 °C	Air-cooled plant, (C. S. Turchi and Heath 2013)

* SAM reports temperatures at the solar field outlet. The temperature at the steam turbine inlet will be slightly lower due to heat losses and, for some models, the steam generation heat exchanger approach temperature.

The storage cost input was formerly missing from the molten-salt Fresnel model and is added at a value that is scaled from the molten-salt power tower model based on the estimated ratio of TES temperature differentials. Molten-salt power towers have a TES $\Delta T = 284$ K, compared the assumed Fresnel value of 232 K. The resulting Fresnel cost input is $26*(284/232) = \$32/kWh_{th}$. The direct-steam linear Fresnel model does not include TES. Other changes to the molten-salt Fresnel model are due to indexing or harmonizing with the other CSP models.

CSP Generic

The default case for the CSP Generic model is patterned after the molten-salt power tower. This model is useful for estimating the performance and cost of user-defined systems that do not match any of SAM's CSP configurations.

7 Discussion

This NREL analysis has used DFMA as the main tool for estimating the manufacturing costs associated with the solar field components of two state-of-the-art parabolic trough collectors—the SkyTrough and the Ultimate Trough. The flexibility and strength of DFMA comes from allowing the user to create his or her own components and assemblies. In the case of the SkyTrough and Ultimate Trough, the majority of the mechanical components could be simulated within the tool. This analysis follows the methodology used in a similar study NREL undertook for a modern heliostat design in 2013.

The use of DFMA is well suited for the analysis even though there were certain limitations that needed resolution. The detailed databases in the DFMA tool have cost data for a range of manufacturing processes (e.g., injection molding, stamping) and machining steps (e.g., cutting slots in material); however, the cost of materials is left to the user's discretion. For example, during the investigation it was found that the raw aluminum alloy material costs in DFMA were approximately \$1.70/lb and needed to be updated to current market prices. The alloy cost of aluminum as of August 2015 was approximately \$1.03/lb. For the SkyTrough, the majority of the frame parts utilized structural aluminum; changing the raw material cost inputs in DFMA had a significant impact on the resulting costs. The DFMA tool does not track commodity costs and care must be taken to apply current raw material costs.

The DFMA analysis highlighted components and processes that benefit from large volume production. This tactic was applied generally to components that required tooling that could be amortized over the increasing volume of production. An example space frame connector in the SkyTrough dropped from \$1,000 to \$50 per part when production was increased from 15 to 15,000 (raw material cost was unchanged). This production-volume effect is dramatically less for items available from stock suppliers. For example, the cost of a steel square box tube cantilever arm for the Ultimate Trough will not significantly decrease with required quantity. This is because the material cost already represents more than 95% of the total part cost. The increase in manufacturing volume will benefit the setup times, batch sizes, and the move to increased automation but will reduce the part's overall cost by a few cents even at a quantity of 500,000.

The DFMA analysis performed here can be considered a "should cost" assessment. That is, it answers the question: what should the component cost when based solely on material and manufacturing steps? The next level of sophistication using DFMA is to examine "product costing" and "product simplification." In this type of investigation, researchers would study an overall design that employs alternative manufacturing processes, materials, and techniques; the objective would be to reduce part count and material content (Boothroyd Dewhurst Inc. 2015a). These progressive steps can significantly cut the overall cost of systems. One example was demonstrated by DFMA developer Boothroyd Dewhurst. In more than 500 surveys of its industrial users, the developer found that on average companies could save between 30%-50% of the final product cost (Boothroyd Dewhurst Inc. 2015b).

8 Conclusions

8.1 SkyTrough Estimates

The SkyTrough analysis estimated the potential installed cost for an SF of 1500 SCAs as $170/m^2, which included a tooling investment of $270,000 amortized over the production run and tool life. The investigation found that trough installed costs were sensitive to factors such as raw aluminum alloy cost, steel cost based on source country, and production volume. For example, in the case of the SkyTrough, the installed cost would rise to nearly $210/m^2 if the aluminum alloy cost was $1.70/lb instead of $1.03/lb. Accordingly, one must be aware of fluctuations in the relevant commodities markets to track system cost over time.

Though the SkyTrough is a commercial design, SkyFuel has suggested that SkyTrough's primary market moving forward will likely be smaller CSP plants and industrial thermal applications that take advantage of SkyTrough's assembly protocols that do not require complex and expensive jigs. This does not negate SkyTrough's suitability for larger CSP plants, but rather highlights its advantages for smaller size projects.

Going forward, both SkyFuel and FLABEG FE place great emphasis on trough plants using molten salt as the HTF and thermal storage media. SkyFuel is developing the SkyTrough DSP (Dispatchable Solar Power) as a parabolic trough collector that is designed specifically for large-scale power generation (Hoste 2015). Much like the design philosophy behind the Ultimate Trough, the SkyTrough DSP has been optimized to decrease the components in the SF and can use either synthetic oil or molten salt as the HTF (White et al. 2012; Schuknecht, Viljoen, and Hoste, n.d.). The SkyTrough DSP has an aperture width of 7.6 m and an SCA length of 150 m (Hoste and Schuknecht 2015). To date, the SkyTrough DSP has been constructed as a single test module at the SkyFuel Colorado test site. NREL's visit to the SkyFuel test facility in Arvada, Colorado, was extremely helpful to gain insight into the collector design.

8.2 Ultimate Trough Estimates

The estimated installed cost for the Ultimate Trough was only slightly higher than the SkyTrough estimate at $178/m^2, which includes a tooling investment of $482,000 and an assembly facility of $11.6 million. Both of the latter are amortized over the required production volume. Considering the size and overall cost of a 700-SCA Ultimate Trough SF, two parallel production lines in a fully covered assembly facility—each with the specific torque box, module, and mirror jigs—would be justified for a full CSP plant. In comparison, the developer estimated that for an SF of 68 Ultimate Trough loops using synthetic oil for the HTF the module assembly line was on the order of €5M (~$6.7M). This analysis focused on the cost of the collector structure, and the estimate of assembly jig costs was somewhat limited. Further investigation is required to get a better understanding of the assembly facility needed for the Ultimate Trough. This was one factor that led to greater confidence in the estimate for SkyTrough.

The uncertainty of NREL's Ultimate Trough analysis was regarded as higher than for the SkyTrough because of less access to detailed design information and the hardware itself. Accordingly, it is estimated that the Ultimate Trough installed cost could be as high as $200/m^2. FLABEG FE estimated that an equivalent-sized Ultimate Trough SF could be 20%-25% less than a EuroTrough SF (Schweitzer et al. 2014). Comparing NREL's installed cost to a published estimate by the developer, there is good similarity between the two estimates. For example, SBP estimated that for an SF of 68 loops, the installed cost (excluding licensing costs) was approximately €144/m^2 or \$161/m^2 (SBP 2013). Compared to the SBP estimate of \$161/m^2, the NREL estimate of \$178/m^2 is within about 10%.

The investigation found that the Ultimate Trough SF was sensitive to steel prices and also special components costs such as the receiver tubes. Discussions with the manufacturers of the receiver tubes have noted that the 70-mm OD receiver tubes used for the Ultimate Trough molten-salt application must be manufactured from more advanced materials that can operate up to 550°C. These tubes have been produced and tested though they were still considered a nonstandard item as of 2015—mainly because there are no large commercial CSP parabolic trough plants that utilize a molten-salt HTF. As such, the cost estimate used by NREL for the 70-mm receiver tubes is based on the assumption that a significant market exists for such receivers. The quote provided to NREL assumed a yearly order of 42,000 70-mm receiver tubes. Without a strong project pipeline requiring the 70-mm design, the internal investment costs to make these receiver tubes are prohibitive.

The two-SCA test loop of the Ultimate Trough in Harper Lake, California, has been operating with synthetic oil since January 2013. Initial results of the thermal output of the loop are reportedly on par if not better than FLABEG's performance model estimates (SBP 2013). NREL performed an independent assessment of the Ultimate Trough test loop and found the measured thermal efficiency to be within the 95% confidence level of the FLABEG theoretical model (Zhu and Neises 2015). The continued operating success of the current test loop has prompted FLABEG FE to further the development and testing of the Ultimate Trough. Discussions with FLABEG FE indicate that the company is considering building up to two molten-salt Ultimate Trough test loops as early as 2016. The development of molten-salt HTF troughs is viewed as a key path toward greater competition with power tower CSP designs.

8.3 SAM Update

Compared to the Ultimate Trough, the greater level of detail available for the analysis and the further commercial development associated with the SkyTrough led to its selection as the default parabolic trough within SAM's Physical and Empirical Trough Models. The SkyTrough uses the Reflectech PLUS polymer film. Testing has shown the film to be very durable; however, some project stakeholders may consider this a higher risk than use of conventional back-surface glass mirrors. Such subjective evaluations can be captured by adjusting SAM's financial inputs or allocating reserves for future maintenance if the user sees fit. Relative to NREL's 2010 study of a commercial-scale CSP parabolic trough reference plant, the SkyTrough's installed cost was approximately 43% lower than the previous value (C. Turchi 2010) and was 37% lower than NREL's revised number from 2012. Other non-solar-field costs within SAM were updated by indexing for inflation. Changing these values in SAM's current default Physical Trough Model leads to a change in the estimated real levelized PPA price from 14.9 ¢/kWh to 13.9 ¢/kWh. Note that the SAM default case includes a 30% ITC.

In addition to updating SAM's parabolic trough models, this report updates the costs in other SAM CSP models to 2015 and switches all CSP models to assume air-cooling as the default power cycle cooling design.

With the trend toward higher efficiency and operating temperatures, a future update to SAM would benefit from development of a molten-salt trough case. Such a case could use the Ultimate Trough or perhaps the SkyTrough DSP as the representative solar collector.

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Appendix – SAM Screenshot