Manufacturing Cost Analysis of Advanced Parabolic Trough Collector

Preprint

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Manufacturing Cost Analysis of Advanced Parabolic Trough Collector

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Abstract. The research team performed a detailed bottom-up manufacturing cost estimate for an advanced parabolic trough design — the Solar Dynamics Sunbeam-MT (Sunbeam Mid-Term). This includes all components for manufacturing and assembly in a manufacturing facility (e.g. space frame and arms), and the purchased parts (e.g. mirrors and receiver tubes). Estimates of the construction and assembly activities have been made to then determine an estimated installed cost. Prior analysis has already undertaken detailed bottom-up manufacturing, assembly, and construction analysis for the Ultimate Trough from schlaich bergermann partner (sbp), and this work updates the solar field cost estimates based on a similar aperture area as the SunBeam-MT. For this analysis, the Ultimate Trough is considered the commercial parabolic trough and the Sunbeam-MT as the advanced parabolic trough. For similarity, both the Sunbeam-MT and the Ultimate Trough have been modelled with a solar field with approximately 800,000 square meters (m^2) in aperture area —the equivalent of a large CSP plant. The analysis has found a potential installed cost estimate of the Sunbeam-MT could be $\$120/m^2$ but must be built at scale to confirm this estimate. Compared to prior analysis, the commercial Ultimate Trough using U.S. conditions, has reduced in installed cost from $\$178/m^2$ to $\$152/m^2$. Both designs could be even cheaper with Chinese steel.

INTRODUCTION

Concentrating solar power (CSP) technologies capture the heat of the sun to drive a thermo-electric power cycle. The most widely deployed CSP technology currently uses parabolic trough collectors. As of 2020, of the 6,128 megawatts electric (MWe) of global installed CSP capacity, greater than 4,000 MW of operational parabolic trough plants are present [1], [2]. The United States is home to 3 operational power tower plants totaling 392 MWe (Ivanpah project) and 14 operating parabolic trough projects totaling 1,746 MWe [3]. In 2010, the National Renewable Energy Laboratory (NREL) established a baseline cost for parabolic trough technology in the United States by working with Worley Parsons in designing and costing a 100 MW parabolic trough plant with six hours of thermal energy storage (TES) [4]. In 2015 NREL published a detailed costing study of an advanced collector and a near commercial collector. These were the SkyFuel SkyTrough and the sbp Ultimate Trough parabolic trough collectors [5]. The prior Ultimate Trough work has been updated alongside a detailed bottom-up estimate for another next-generation advanced collector. Both collectors in this study are large aperture troughs.

A new collector technology emerged from the United States Department of Energy (DOE) funded Advanced Trough with Lower-cost System-Architecture (ATLAS) project [6], which aimed to reduce the cost of large parabolic trough fields. The ATLAS project produced two collector design variants known as the SunBeam-NT (near-term) and SunBeam-MT (Mid-Term). For this paper, the Ultimate Trough is considered the commercial parabolic trough and the SunBeam-MT as the advanced parabolic trough. The research team performed a detailed bottom-up manufacturing cost estimate for the Sunbeam-MT. This includes all components for manufacturing and assembly in a manufacturing facility (e.g., space frame and arms), and the purchased parts (e.g., mirrors and tubes).

ANALYZED PARABOLIC TROUGHS

The DOE funded ATLAS project generated two collector design variants [6], both leveraging Solar Dynamics patent-pending new "SunBeam" helical steel space frame architecture. Compared to previous state-of-the-art large-aperture steel space frame troughs such as the Abengoa SpaceTube (8.2 x 16m per SCE) [7], the SunBeam-NT is similar in most respects, retaining similar aperture width and mirror shape, similar steel component and fastener types, and similar assembly strategy. The SunBeam-NT uses a more efficient frame layout which enables lower mass content by approximately 30%, through the reduced number of parts and fasteners per m^2 aperture, and a 50% longer concentrator length (8.2 x 20m per SCE). The SunBeam-MT version is based on the same space frame truss as the NT, but it is 25m long to further reduce pylon and foundation counts and it employs a new innovative mirror support structure design and mirror attachment, which eliminates the need for adjustable mirror attachment brackets and costly onsite bracket alignments. Both NT and MT variants use industry-standard 4mm glass mirror technology common in other parabolic trough designs such as the EuroTrough and the Ultimate Trough.

The SunBeam-NT advanced collector design is currently deployed at the Solar Technology Acceleration Center (SolarTAC) facility in Colorado as a full-scale prototype (Figure 1 left). At the time of writing, the Sunbeam-MT has yet to be deployed in a large-scale CSP plant. The key subsystems for the SunBeam-MT are the receiver tubes, receiver supports, mirror panels, riveted arm assemblies, the space frame, torque transfer plates, drives and controls, foundations, drive pylon and regular pylons. The presented analysis for the SunBeam-MT includes estimated field assembly and construction activities. These estimates are based on detailed work undertaken for DOE on the ATLAS trough where the construction, tooling investments and solar field assembly activities were estimated for a similar sized ATLAS trough solar field [8].

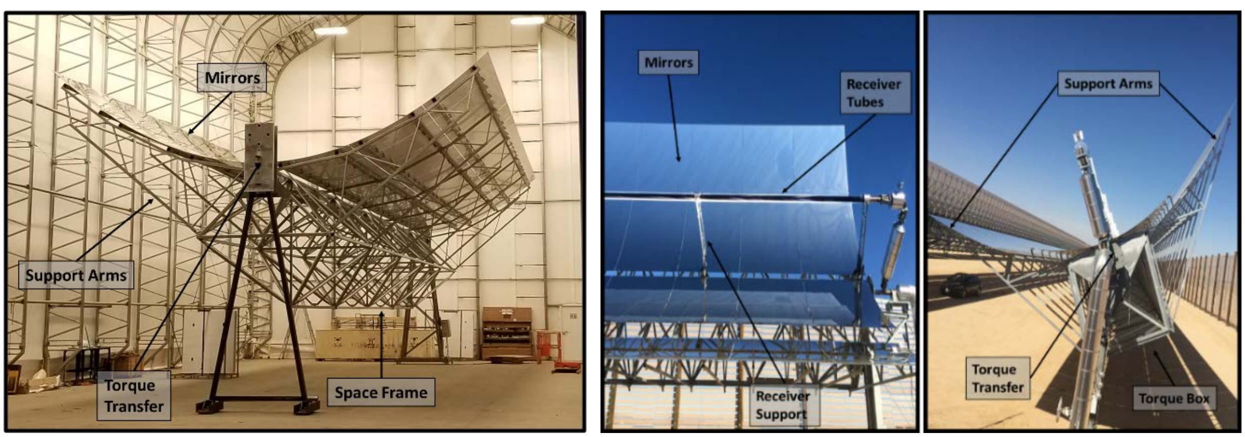

FIGURE 1. Left: Full scale SunBeam Near-Term (NT) prototype at the SolarTAC facility, Colorado. *Credit: Solar Dynamics.* Right: Full-scale integrated Ultimate Trough in California. *Credit: sbp.*

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, with the support of the German government and the German Aerospace Center (DLR) [9], [10]. Figure 1 right shows the Ultimate Trough installed at the Harper Lake site in California. The key sub-systems for the Ultimate Trough are the cantilever arms, torque box, mirrors, pylons, foundations, receiver tubes, receiver supports, end plates, swivel joints, drives, controls, and sensors. It is important to highlight the Ultimate Trough is considered fully commercially ready and deployed. The Duba Green Power Plant is the first Ultimate Trough commercial realization in the Kingdom of Saudi Arabia (KSA), where 124 solar collector assemblies (SCAs) are installed for a field aperture area of approximately 170,000 m^2 [10]. The Ultimate Trough solar field is part of the Duba Green Integrated Solar Combined Cycle Power Plant, where the solar field provides a heat input of up to 50 MWe (or about 120 MW thermal, MWth) to the natural gas combined cycle of 565 MWe [11].

APPROACH AND METHODOLOGY

Key Assumptions and Limitations

The aim for the Sunbeam-MT bottom-up costing has been to create a representative case for the design at a commercial scale assuming manufacturing and assembly occurs in the United States. Similarly, for the Ultimate Trough, the aim of this analysis is to update the original analysis [5], e.g., by scaling the 1.1 million m^2 aperture solar field to 0.8 million m^2 to be similar in size to the modelled Sunbeam-MT solar field. There have been many key assumptions needed for this bottom-up cost modelling. The most important assumptions are discussed below.

Industrial experience with commercial projects has shown that when a project-based solar field is designed, the solar field must consider site-specific considerations such as land and soil conditions as well as wind loading. For example, at the Duba Green Power Plant, where the Ultimate Trough was deployed in its first commercial realization in the KSA, due to a highly corrosive environment near the Red Sea, design changes such as the use of very high corrosion protection for the steel structures were needed [10]. Inclusion of these factors leads to changes in the collector structures across the solar field, and therefore drives cost based on the materials used. Another example, typically reinforced collectors can be used in the solar field along the periphery where higher strength and torsional rigidity are required to offset the higher wind loads. When the amount of structural steel for a 50 MW solar field (that can also provide sufficient energy for 7hrs of TES) is considered, it was found that a change in wind speed from 34m/s to 38m/s lead to an increase in approximately 16% of additional steel needed (i.e. 14,450 tons instead of 12,500 tons) [12]. However, the NREL analysis examined only the standard internal field solar collector elements (SCEs) for the Sunbeam-MT and Ultimate Trough designs, rather than a mix of perimeter and internal SCEs and SCAs. A SCE is the smallest modular sub-section of a SCA.

A plant of 90 MWe with six hours of TES was selected as the representative plant size, because it provides optimal fit on a 1-mile square parcel of land. This is similar to prior analyses [5], [13] and representative of current projects. The approximate aperture area is 800,000 m^2 and the energy yield would be dependent on the assumed solar multiple, location and associated Direct Normal Irradiance (DNI) resource. The exact solar field size is not critical, but it was necessary to specify a size that could be used for the production volume calculations within the Design for Manufacturing and Assembly (DFMA) software. For the analyzed collectors, the Sunbeam-MT and the Ultimate Trough, even though the solar field aperture areas are similar (~800,000 m^2), the thermal output of both solar fields may be significantly different. Independent performance tests of both would be needed for a performance comparison. This study is only looking at the estimated installed cost of the solar field. The parabolic trough 'Solar Field' is made up of: mirrors, receiver tubes and fittings, solar collector frame, collector assembly components e.g. rivets, foundations and support structures, sensors and controls, electrical cabling, installation labor and assembly infrastructure (e.g. temporary building, jigs and crane rental). Notably, the header piping and the HTF that are utilized in the solar field were excluded from the analysis; but the receiver cost is included within the solar field subsystem. The Sunbeam-MT and Ultimate Trough solar fields have been estimated using 89mm receiver tubes which would contain synthetic oil as the HTF, even though both can utilize molten salt [5], [14]. For this analysis, \$2019 is used.

Bill of Materials (BOM) Development

The BOM for the Solar Dynamics Sunbeam-MT design is critical and underpins the bottom-up cost analysis. The BOM for the reference case (without spare parts) consisted of the total number of components and sub-assemblies that would be required to build the SCEs and then SCAs, which would then constitute the assemblies needed for the specified 800,000 m^2 solar field. For a project scenario, the BOM would include the complete set of parts (including a certain percentage of spare parts), instrumentation, materials, and pre-assembled parts that would be used by the Engineering Procurement & Construction (EPC) contractor to assemble the solar field. The Sunbeam-MT was analyzed using proprietary engineering drawings, computer aided design (CAD) models and BOM provided by the manufacturer. An understanding of the individual components, estimated dimensions, tolerances, materials used, and the quantity involved (e.g., the number of reflective panels) is the foundation for the manufacturing and sub-assembly analysis.

Solar Dynamics have provided to NREL recent quote estimates for mirrors, receiver tubes, interconnects, drive hydraulics, controls, transportation in the U.S. and sensors. Steel quotes were also provided for reference and comparison to the Design for Manufacturing (DFM) steel estimates for the SunBeam-MT collector structure. Due to a similar collaborative effort with sbp, the detailed BOM and DFMA for the Ultimate Trough 1.1 million m^2 from prior analysis [5] has been updated to approximately 0.8 million m^2 of aperture area. The prior analysis of the Ultimate Trough was thoroughly reviewed and re-calculated using the same steel and labor rates as those used for the SunBeam-MT. Where possible manufacturing efficiencies were utilized to reduces costs.

The NREL study only considered an available commercial design (i.e., the Ultimate Trough) and the advanced Sunbeam-MT trough, see Table 1 for further details. Note, as highlighted in Table 1 the Ultimate Trough design can utilize either 6 of the standard 4.06m receiver tubes or 5 longer 4.88m receiver tubes. With consultation with sbp, for this analysis it was decided to utilize the 4.88m version, which has an 8% increased per unit receiver cost, but fewer units per SCE, and thereby reducing the overall cost. The Sunbeam-MT is presently configured to use 6 receiver tubes per SCE in all scenarios.

TABLE 1. Commercial and Advanced Parabolic Troughs Examined in this study

Property	**Ultimate Trough [15]**	**Sunbeam Mid-Term (MT)**
Manufacturer	sbp (Germany)	Solar Dynamics (USA)
Reflector type	4-mm glass	4-mm glass
SCA length (m)	247	200
SCEs per SCA (standard)	10	8
Receivers per SCE	5	6
Aperture width (m)	7.51	8.20
SCE length (m)	24.5	24.8
SCA aperture area (m^2)	1,715	1,576
Frame design	Torque box	Spaceframe
Primary frame material	Steel	Steel
Total number of SCAs	468	510
Solar field total aperture area (m^2)	802,620	803,760

Design for Manufacture and Assembly (DFMA)

A key tool in the analysis has been a suite of software tools called DFMA, from Boothroyd Dewhurst. This tool was used in a previous NREL analysis from which the installed cost of a state-of-the-art and near-commercial parabolic troughs were determined [5]. Other NREL analysis also utilized DFMA for determining detailed costs [16], [17]. The DFMA software package is used industry-wide and has two parts: DFM and Design for Assembly (DFA). For this analysis, the version of the DFM software was 3.1.1.173 and for the DFA software it was 10.2.2.257 [18]. 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 most of the components within the BOMs to model the troughs as if it were to be manufactured in commercial quantities needed for a large solar field. 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. Specialist components such as receiver tubes or mirror panels are beyond the DFMA capabilities and therefore their costs where based on quotations.

DFM allows the user to produce a detailed "should-cost" number that is based on what a component should cost from the manufacturer; this cost is based on material, process steps, machine setup time, and tooling if needed. Tooling investment is calculated for special processes such as stamping and considers tool wear and life based on the life volume of the parts needed for the BOM. Note, U.S. labor rates for the machining processes have been used. DFA was then used to assemble (e.g., weld and rivet) the components together into sub-assemblies. DFMA was used for the collector frame structure and manufacturing estimates for the pylons. A key feature of the DFMA tool is the built-in ability to change the life volume of the manufactured parts to compare the effects of small-scale production versus commercial scale. For example, increasing production volume from 20 to 20,000 for a SunBeam-MT stamped plate caused the final manufactured part cost to drop from approximately $1,000/part to approximately $10/part. This is because the part specific tooling investment is amortized over greater volumes.

MANUFACTURING AND INSTALLATION COST ANALYSIS

SunBeam-MT Trough Installed Cost Analysis

The manufacturing cost analysis includes machining, in-house assembly and purchased items, assuming a production volume of 510 SCAs, which is representative of a solar field of approximately 803,760 m^2 of total field aperture area. This solar field, which occupies approximately 1 square mile of land area, is suited for a 90-MWe plant with 6hrs of TES. It is estimated that the overall installed cost for solar field design (of 510 SCAs) is approximately $120/$m^2$ of aperture area (Figure 2 left). The manufacturing cost also includes an estimated $890,000 investment cost to purchase tooling specific to the manufacturing of the steel components for the space frame, support arms, and receiver supports. When the total manufacturing tooling investment (e.g. for stamping dies) is amortized over 510 SCAs, it adds less than $1.1/$m^2$ to the manufactured cost. The installed cost as a proportion of the total cost (including purchased parts) is shown in Figure 2 right.

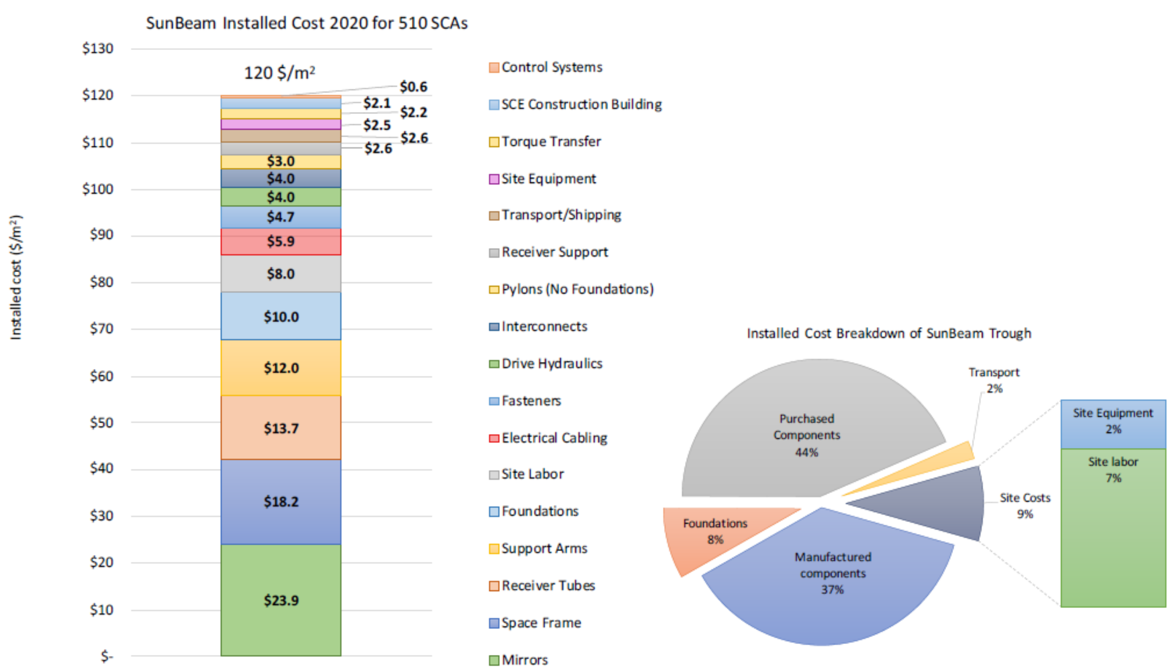

FIGURE 2. Total installed cost for Sunbeam-MT trough for 510 SCAs

This cost includes the sub-assemblies e.g. arms, which would be assembled in the manufacturing plant after component manufacturing. Utilizing detailed estimates from the Abengoa ATLAS trough [8], which the Sunbeam-MT is derived from, solar field construction and in-field activities have been estimated. As seen in Figure 2, the largest contributors to the installed cost are the mirrors (20%), the space frame (15%), and the receiver tubes (11%). The support arms (10%) are the next most massive steel structures after the space frame. The site labor costs (7%) quantify the total expected labor costs required to assemble and install the very similar ATLAS trough in a previous analysis [8]. The NREL analysis does not account for robotic riveted assembly of the space frame and arms of the SunBeam-MT which is proposed by Solar Dynamics. Discussions with Solar Dynamics have confirmed the NREL assumption for manual power riveting instead of robotics to set the baseline for the SunBeam-MT.

The foundation costs are variable due to site specific considerations such as soil quality and expected wind loads. The foundation costs (8%) were therefore set at a fixed median value of $10/m^2 based on discussion with Solar Dynamics and similarity to prior analysis. The pylons where calculated separate from the foundation costs. All other categories contribute less than 7% to the total installed cost. The large contribution by the fasteners category alone speaks to the riveted construction employed to reduce assembly time and costs. The transportation and shipping costs are based on domestic shipping within the USA calculated based on percentages of vendor quotes provided by Solar Dynamics. The SunBeam-MT trough utilizes a balance of purchased components and manufactured components as can be seen in the pie chart. The site costs are a balance between labor and equipment.

Ultimate Trough Installed Cost Analysis

The manufacturing cost analysis includes machining, in-house assembly and purchased items, assuming a production volume of 468 SCAs, which is representative of a solar field of approximately 802,620 m^2 of total field aperture area. Figure 3 left shows the breakdown of the Ultimate Trough by cost category, and right the proportional cost. It is estimated that the overall manufactured cost for solar field design (of 468 SCAs) is approximately $152/m^2.

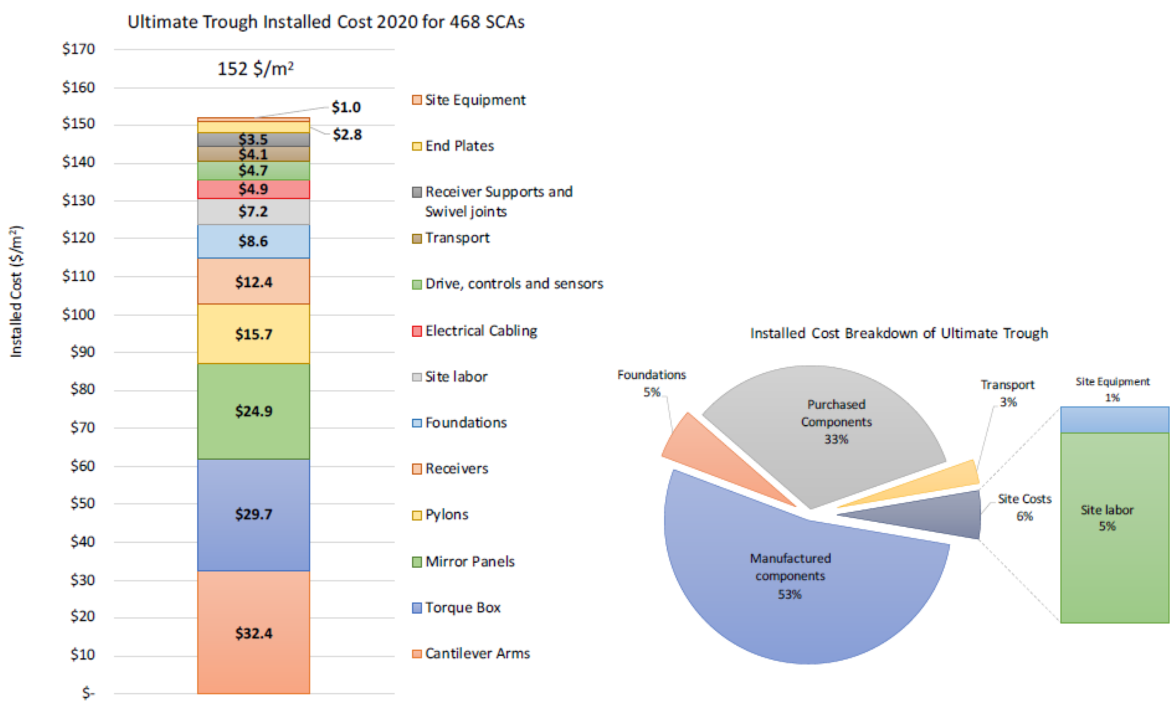

FIGURE 3. Total installed cost for Ultimate Trough for 468 SCAs

The key contributors to the total cost are the cantilever arms (21%), torque box (20%) and the mirror panels (16%). The pylons (10%) are the next most massive steel component. Just as in the SunBeam, the foundation cost is discrete from the pylons. A fixed foundation cost of $10/m^2 was adjusted to $8.6/m^2 (as a conservative estimate); due to decreased foundations facilitated by the torque box structure allowing for longer spans between pylons [15].

The Ultimate Trough design also has the flexibility of using either six standard 4.06m long receiver tubes or 5 longer 4.88m receiver tubes which are 8% more expensive, based on sbp quotes. The decrease in total number of receiver tubes nets a decrease in the total cost reduction of $1.5/m^2$. In the Ultimate Trough analysis site labor costs are estimated as 5% of the installed costs. It should be noted that the field assembly labor costs are included within the DFMA model for the Ultimate Trough which differs from the SunBeam-MT model where these are part of the site labor category. The tooling investment (~$11 million (M) in total [5]) is primarily for site fixturing to allow for assembly of the torque box steel frame and the fixture for the subsequent installation of mirrors to the frame.

The prior estimated manufactured and installed cost (in $2015) for the Ultimate Trough was $178/m^2$, which included an assembly facility of $11 M amortized over the required production volume [5]. This did not account for a 5% site labor applied to the manufactured and purchased components which would have increased the installed cost to $187/m^2$. The current analysis shows a decrease of 15% in the installed cost compared to the prior analysis ($178/m^2$ compared to $152/m^2$). The primary decrease is in the receiver tube costs e.g. by approximately $12/m^2$. Secondarily, manufacturing process adjustments withing the DFMA models have reduced costs of some manufactured steel parts e.g. by approximately $7/m^2$. In the 2020 model U.S. steel prices have been utilized. It is important to highlight that the shipping cost have therefore been changed from international in the 2015 model to domestic within the USA for the 2020 model. This change in shipping calculation also contributes to the decrease in cost.

DISCUSSIONS & CONCLUSIONS

The current analysis for the SunBeam-MT advanced parabolic trough estimates the installed cost at $120/m^2$, though it has yet to be demonstrated at scale in the field to confirm this estimate. The overall Solar Dynamics strategy is to demonstrate and commercialize the NT version, then integrate MT-version design features into commercial systems and deploy the systems at scale. Once commercially deployed, the cost reduction potential of the SunBeam-MT can be verified. One more key design aspect of the SunBeam-MT is that it has been designed for robotic riveted assembly [14]. The NREL analysis does not account for robotic assembly and therefore the baseline cost could be reduced further. Solar Dynamics proposed robotic assembly for two or more 800,000 m^2 solar fields [8], thus that has been left out from this analysis. The use of fully automated robotic assembly could save up to 10% in assembly labor cost if all assembly processes of the space frame, arms and receiver supports, are switched to robotic riveting. This could lead a further 3% saving in total installed cost of the SunBeam-MT system. The SunBeam-MT has yet to be installed at scale and therefore the construction cost estimates have potential uncertainty associated with them. Future work looks to address increasing the accuracy of the construction cost estimates. Unitization of Chinese steel including shipping could also further reduce the calculated costs. The SunBeam-MT can utilize molten salt in the receivers and solar field, and would act as a way of reducing the solar field size and therefore further overall solar field cost [14].

Our current analysis calculates that the commercial parabolic trough, represented by the Ultimate Trough has an estimated installed cost of $152/m^2$, which is an 11% decrease overall in cost compared to the 2015 results [5]. This estimated cost could be further reduced by utilizing Chinese steel, which is likely for most project situations. The 11% cost reduction is primarily driven by the receiver tubes decreasing in cost, which all troughs now benefit from. Relative to the 2015 results, the receiver tubes for the Ultimate Trough today have dropped by 49% (e.g. $25/m^2$ compared to $12/m^2$). The Solar Dynamics 2020 analysis has also benefitted from these lower cost receivers, and Solar Dynamics has provided quotes for their receiver tubes to verify the cost reduction relative to last time. Receiver tubes for CSP plants are made in a few facilities in the world, where these manufacturing plants have amortized their equipment, which could explain receiver tube cost reduction. The extent of future receiver tube decreases requires investigation.

The NREL Ultimate Trough reference is approximately 800,000 m^2 compared to 170,000 m^2 (Duba Green Power Plant), as such discussions with sbp indicate that the Duba solar field due to wind loads, corrosion prevention requirements, and its smaller scale than this study's, may not reach the estimated cost of $152/m^2$. Work from DLR where the Ultimate Trough is used as today's reference system, found that the solar field cost in $2018 could be approximately $127/m^2$ in Morocco, albeit for a larger solar field [19]. This solar field like the NREL analysis includes: the collector structure, the pylons and foundations, the mirrors, the receivers, drives and electricals, but not the site preparation, HTF in the solar field and the HTF system. With a 100 Price Index for Morocco and a Price Index of 114 for the U.S. [19], the U.S installed cost for the Ultimate Trough could be roughly $145/m^2$. Improvements to the Ultimate Trough (e.g. molten salt and 10m aperture) are not incorporated here and could reduce cost further [19].

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REFERENCES

[1] SolarPACES, "CSP Projects Around the World," *Solarpaces*, 2020. https://www.solarpaces.org/csp-technologies/csp-projects-around-the-world/ (accessed Mar. 23, 2020).

[2] C. S. Turchi, J. Stekli, and P. C. Bueno, "11 - Concentrating Solar Power," in *Fundamentals and Applications of Supercritical Carbon Dioxide (sCO_2) Based Power Cycles*, K. Brun, P. Friedman, and R. Dennis, Eds. Woodhead Publishing, 2017, pp. 269–292.

[3] NREL, "Concentrating Solar Power Projects in the United States," n.d. https://solarpaces.nrel.gov/by-country/US (accessed Mar. 28, 2020).

[4] C. Turchi, "Parabolic Trough Reference Plant for Cost Modeling with the Solar Advisor Model (SAM)," National Renewable Energy Laboratory, Golden, CO, Technical Report NREL/TP-550-47605, Jul. 2010. doi: 10.2172/983729.

[5] P. Kurup and C. Turchi, "Parabolic Trough Collector Cost Update for the System Advisor Model (SAM)," NREL, Golden, CO, Technical Report NREL/TP-6A20-65228, Nov. 2015. Accessed: Mar. 23, 2020. [Online]. Available: http://www.nrel.gov/docs/fy16osti/65228.pdf.

[6] DOE, "PROJECT PROFILE: Abengoa Solar, LLC – ATLAS," *Energy.gov*, 2014. https://www.energy.gov/eere/solar/project-profile-abengoa-solar-llc-atlas (accessed Mar. 23, 2020).

[7] P. Marcotte and K. Manning, "Development of an advanced large-aperture parabolic trough collector," 2014.

[8] D. O'Rourke and A. Farr, "Improved Large Aperture Collector Manufacturing," Abengoa Solar LLC, 2015. Accessed: Mar. 23, 2020. [Online]. Available: https://www.energy.gov/sites/prod/files/2016/04/f30/Improved%20Large%20Aperture%20Collector%20Manufacturing%20-%20Abengoa%20Solar%206357.pdf.

[9] A. Schweitzer *et al.*, "Ultimate Trough ® – The Next Generation Collector For Parabolic Trough Power Plants," presented at the SolarPaces 2010, 2010, Accessed: Sep. 12, 2020. [Online]. Available: https://www.researchgate.net/publication/282859075_ULTIMATE_TROUGH_R_-_THE_NEXT_GENERATION_COLLECTOR_FOR_PARABOLIC_TROUGH_POWER_PLANTS.

[10] K.-J. Riffelmann, A. Schweitzer, G. Weinrebe, and M. Balz, "Planning and building the first ultimate trough collector field in the Kingdom of Saudi Arabia," *AIP Conference Proceedings*, vol. 2126, no. 1, p. 040002, 2019, doi: 10.1063/1.5117582.

[11] SBP, "Ultimate Trough DUBA," 2017. https://www.sbp.de/en/project/ultimate-trough-duba/ (accessed Sep. 12, 2020).

[12] M. Balz and F. von Reeken, "Environmental Loading Conditions for CSP Solar Fields," *Energy Procedia*, vol. 69, pp. 1211–1219, 2015, doi: 10.1016/j.egypro.2015.03.211.

[13] C. Turchi, "Parabolic Trough Reference Plant for Cost Modelling with the Solar Advisor Model (SAM)," NREL, Golden, CO, NREL/TP-550-47605, Jul. 2010. Accessed: Mar. 28, 2020. [Online]. Available: https://permanent.access.gpo.gov/lps125795/47605.pdf.

[14] P. Marcotte, "Advanced Trough with Lower-cost System-architecture (ATLAS)," presented at the SETO CSP Program Summit 2019, Mar. 19, 2019, Accessed: Sep. 15, 2020. [Online]. Available: https://www.energy.gov/sites/prod/files/2019/04/f62/CSP%20Summit2019%20Solar%20Dynamics%20Marcotte%20ATLAS.pdf.

[15] K.-J. Riffelmann, D. Graf, and P. Nava, "Ultimate Trough: The New Parabolic Trough Collector Generation for Large Scale Solar Thermal Power Plants," pp. 789–794, Jan. 2011, doi: 10.1115/ES2011-54657.

[16] P. Kurup, T. Remo, D. S. Jenne, J. Cotrell, and P. O'Connor, "Analysis of Supply Chains and Advanced Manufacturing of Small Hydropower," National Renewable Energy Laboratory (NREL), Golden, CO, NREL/TP-6A20-71511, Jul. 2018. Accessed: Sep. 15, 2020. [Online]. Available: https://www.nrel.gov/docs/fy18osti/71511.pdf.
[17] S. Akar, C. R. Augustine, P. Kurup, and M. K. Mann, "Global value chain and manufacturing analysis on geothermal power plant turbines," National Renewable Energy Lab (NREL), Golden, CO, NREL/TP-6A20-71128, Sep. 2018. Accessed: Sep. 15, 2020. [Online]. Available: https://www.nrel.gov/docs/fy18osti/71128.pdf.
[18] Boothroyd Dewhurst Inc., "Design for Manufacture and Assembly (DFMA) Product Costing and Simplification," 2019. http://www.dfma.com/software/index.html (accessed Mar. 24, 2020).
[19] J. Dersch, S. Dieckmann, K. Hennecke, R. Pitz-Paal, D. Krüger, and P. Ralon, "LCOE Reduction Potential of Parabolic Trough and Solar Tower Technology in G20 Countries until 2030," Jan. 2019, Accessed: Sep. 30, 2020. [Online]. Available: https://www.researchgate.net/publication/337438974_LCOE_Reduction_Potential_of_Parabolic_Trough_and_Solar_Tower_Technology_in_G20_Countries_until_2030.