PARABOLIC TROUGH CSP TECHNOLOGY

STATE OF THE ART AND MARKET OVERVIEW

PROJETO Energia Heliotérmica

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A study produced by the project DKTI-CSP (German Climate Technology Initiative on Concentrating Solar Power), which is managed by the Ministry of Science, Technology and Innovation (MCTI) and the Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. The project focusses on the promotion of climate technologies, in particular Concentrating Solar Power. Its objective is to ensure that required conditions to implement and disseminate Concentrating Solar Power are established in Brazil.

cooperação alemã
DEUTSCHE ZUSAMMENARBEIT

Implemented by: giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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This study has been elaborated by the project DKTI-CSP which is working in the context of the German Climate Technology Initiative. The project is realized by close cooperation between the Brazilian Ministry of Science, Technology and Innovation (MCTI) and the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. The project aims at the creation of the necessary prerequisites for the successful application and dissemination of Concentrating Solar Power (CSP) in Brazil.

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CONTENT

1 INTRODUCTION

In 45 minutes, the sun sends more energy to the earth than humans consume in an entire year. With solar power plants more power can be generated on only 1% of the earth's deserts than fossil fuels produce globally today. The future belongs to whoever succeeds in using these reserves effectively and profitably. Investing here is investing in the market of the future. Our future energy supply must be based on the use of renewable energies. Solar power plants make a valuable contribution to a sustainable and climate-friendly generation of energy.

Parabolic trough power plants are large-scale solar power plants (10 MW to > 100 MW) for the centralized generation of electricity. They consist of a solar field and a power plant unit and can be equipped with a thermal reservoir. In the solar field, solar radiation is transformed into thermal energy. The field consists of many parabolic trough collector units arranged in parallel, which individually and uniaxially track the path of the sun. Thermal energy collected in the solar field can be stored for hours without sunshine.

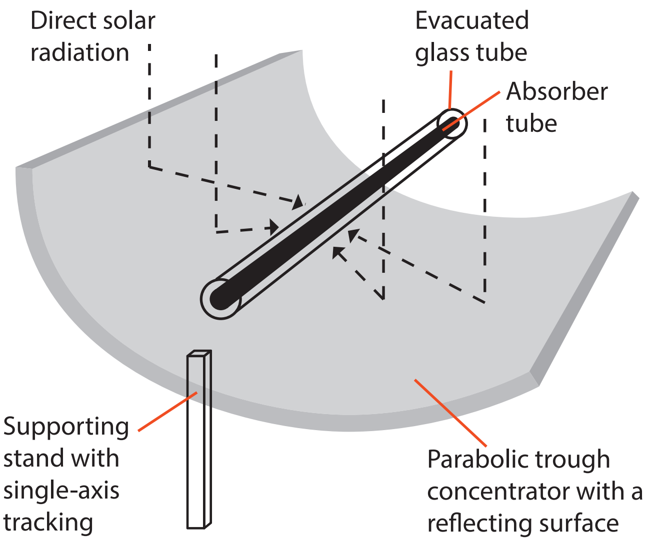


Figure 1: Principle of a parabolic trough

The sun's energy is concentrated by parabolically curved, trough-shaped reflectors onto a receiver pipe running along the inside of the curved surface. This energy heats oil flowing through the pipe, and the heat energy is then used to generate electricity in a conventional steam generator.

Trough designs can incorporate thermal storage — setting aside the heat transfer fluid in its hot phase — allowing for electricity generation several hours into the evening. Currently, all parabolic trough plants are "hybrids," meaning they use fossil fuel to supplement the solar output during periods of low solar radiation. Typically, a natural gas-fired heat or a gas steam boiler/reheater is used; troughs also can be integrated with existing coal-fired plants.

This report is determined to give a comprehensive overview on the international Concentrated Solar Power (CSP) market, specifically on the parabolic trough market. Parabolic troughs are used by the majority of today's solar thermal power plants: Over 4'200 MW are currently under construction or already operating [1]. The report describes the state of the art collectors that are already constructed and integrated into solar power plants all over the world. It also presents a detailed evaluation on technical developments, financial key figures and gives an overview on the 10 biggest main companies that are active in this sector.

Note: All facts and figures are based on the current state of the art information available on the market. If the corresponding information was not accessible to the public, assumptions were made based on own knowledge and calculations.

1.1 HISTORY OF PARABOLIC TROUGH POWER PLANT TECHNOLOGY

This section presents a review of parabolic trough technology models throughout the history of the technology, briefly mentioning their main features, applications and their commercial availability [1].

Parabolic trough power plants constitute the biggest share of the installed Concentrating Solar Power technology. Distinguishing between parabolic trough power plants, Fresnel power plants, solar tower power plants and dish/Stirling systems, the parabolic trough power plants provide over 90% of the capacity of Concentrating Solar Power plant technology that is currently in operation or in construction. Among the planned additional capacity over 50% are parabolic trough power plants.

Figure 2: Solar Collector Field with power block and heat storage tanks in the center (50 MW Andasol plant in Spain)

The first practical experience with parabolic troughs goes back to 1880, when John Ericsson constructed the first known parabolic trough collector. In 1907, the Germans Wilhelm Meier and Adolf Remshardt obtained the first patent of parabolic trough technology. The purpose was the generation of steam. In 1913, the English F. Shuman and the American C.V. Boys constructed a 45 kW pumping plant for irrigation in Meadi, Egypt, which used the energy supplied by trough collectors. The pumps were driven by steam motors, which received the steam from the parabolic troughs. The constructors used parabolic trough collectors with a length of 62m and an aperture width of 4m. The total aperture area was 1,200 m^2. The system was able to pump 27,000 liters of water per minute [2]. Despite the success of the plant, it was shut down in 1915 due to the onset of World War I and also due to lower fuel prices, which made more rentable the application of combustion technologies.

The interest in Solar Concentrating Technology was negligible for almost 60 years. However, in reaction to the oil crisis of the seventies, international attention was drawn to alternative energy sources to supplement fossil fuels, and the development of a number of parabolic-trough systems was sponsored. The US-Department of Energy as well as the German Federal Ministry of Research and Technology began to fund the development of several process heat machines and water pump systems with parabolic trough collectors. Higher fossil fuel prices encouraged the governments to take new measures.

Results of these measures were, for instance, the following:

- Between 1977 and 1982, the company Acurex installed parabolic trough demonstration systems with a total aperture area of almost 10,000 m² in the USA for process heat applications.
- The first modern line-focusing solar power plant was a 150 kWe facility that was built in 1979 in Coolidge/Arizona.9
- Nine member states of the International Energy Agency participated in the project of building demonstration facilities with a rated power of 500 kW at the Plataforma Solar de Almeria, which was put into operation in 1981.
- The first private financed process heat machine with 5580 m² parabolic trough collectors was successfully put into operation in 1983 in Arizona for thermal heating of electrolyte tanks in a copper processing company. These trough systems developed for industrial process heat application were capable of generating temperatures higher than 260°C.

In 1983, Southern California Edison (SCE) signed an agreement with LUZ International Limited to purchase power from the first two commercial solar thermal power plants that should be constructed in the Mojave Dessert in California. These power plants, called Solar Electric Generating System (SEGS) I and II, started operation in the years 1985 and 1986. Later, LUZ signed a number of standard offer contracts with SCE that led to the development of the SEGS III to SEGS IX plants. Initially, the plant size was limited to 30 MW [2].

Figure 3: SEGS II plant at Daggett, CA

After facing regulatory, financial and internal hurdles that resulted in failure of the SEGS X development, LUZ went bankrupt in 1991.

'From 1991 through much of the 90's, no new collector developments took place until the EuroTrough collector project was cost-shared by the EU and a group of European companies. During this period, Flabeg of Germany and Solel Solar Systems of Israel (rising from the ashes of LUZ) supplied mirrors and receivers, respectively, to the operating SEGS plants. Only Solel was in a position at that time to supply a trough solar field, based on the LS-3 design developed by LUZ. Lack of competition in commercial component and system supply was an important concern to developers, institutions and debt providers' [3]. Thus, a group consisting of (in the order of their respective licensing right share) Schlaich Bergermann und Partner GbR, Instalaciones Abengoa SA, Pilkington Solar International GmbH, CIEMAT, DLR and Fichtner with financial support from the European Commission jointly developed the EuroTrough (I) parabolic trough collector[4].

Figure 4: EuroTrough I at the Plataforma Solar de Almería, Spain

In a few years, however, the situation has changed dramatically. As the trough project opportunities in Spain and the Southwest U.S. (in particular, in California) have increased, more companies are applying their expertise to develop commercial trough solar system designs.

In the first half of the year 2004, the Spanish government decided to encourage the development of renewable energy including solar energy by introducing a special feed in tariff (FIT). This new law was an important step starting an impressive development of CSP in Europe and all over the world. Fig. 5 shows the respective shares of CSP technologies used for power plant projects under construction, commissioning or already operational. Projects that have only been announced or that are in the planning stage have not been considered. Obviously, parabolic troughs are the single most important technology used, followed by power towers.

Projects under construction, comissioning or operational

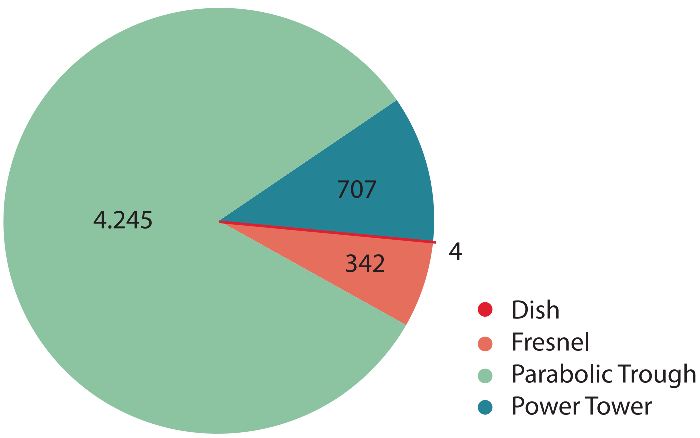


Figure 5: Technology split of global CSP Projects under construction, commissioning or already operational as of December 2013 (data used for chart from [5]); Source: CSP Today Global Tracker, December 2013

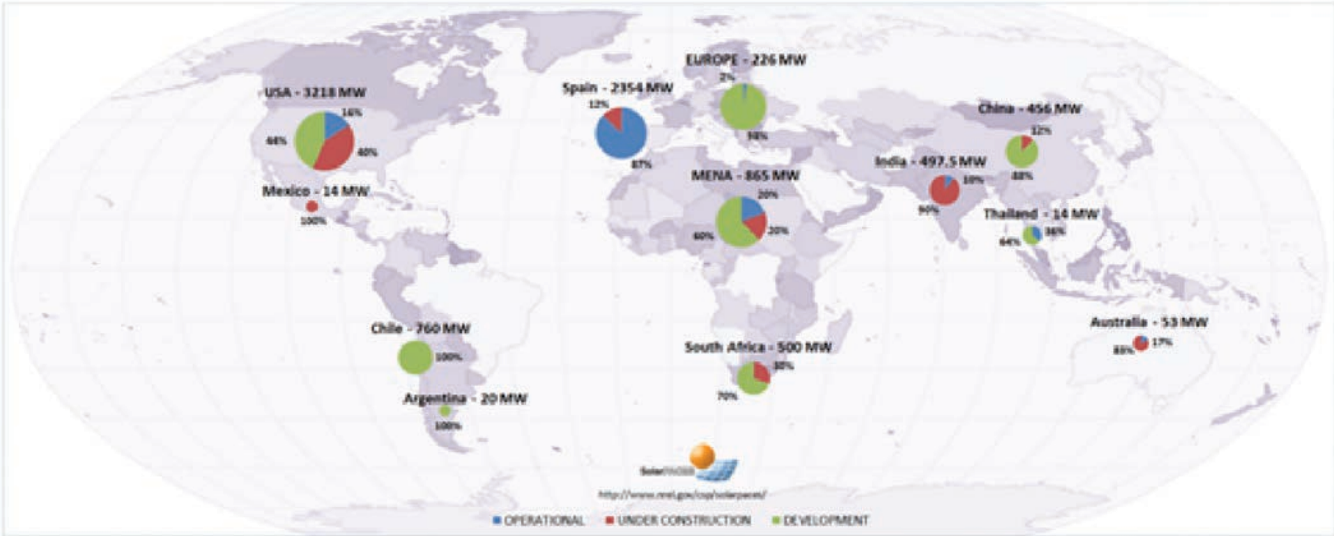


Figure 6: Global CSP Projects as of December 2013 [6]

In Fig. 6 the global distribution of CSP projects can be seen [6]. This chart includes projects under development (in green). Obviously the main market is no longer Spain, as it had been the case for some years. Instead, projects under development and under construction can now be found in Africa, Asia, the US and, last but not least, in South America.

1.2 IMPORTANT ECONOMIC AND TECHNICAL ASPECTS FOR PARABOLIC TROUGH DESIGN

In this chapter, the main technical and commercial aspects for the design of a solar collector field are discussed.

The main technical parameter is efficiency. For efficiency, cosine efficiency is a key constituent. Cosine efficiency is multiplied with the Incidence Angle Modifier (IAM) to consider effects that are not described by the cosine of the incidence angle alone (cf.2.6.4).

In Fig. 7, mean annual cosine efficiency is plotted vs. geographical latitude. Dish collectors are tracking the path of the sun in two axes to make sure that the concentrator's optical axis is always pointing towards the sun. Consequently, cosine efficiency is unity, always and everywhere (red curve).

The heliostats of power tower systems are also equipped with a two-axes tracking system, but because the receiver on the tower is fixed, heliostats do not point directly at the sun, but in the direction of the angle bisector defined by the sun vector and the vector to the receiver. Therefore significant cosine losses can occur; they strongly depend on heliostat location in the solar field (green curves).

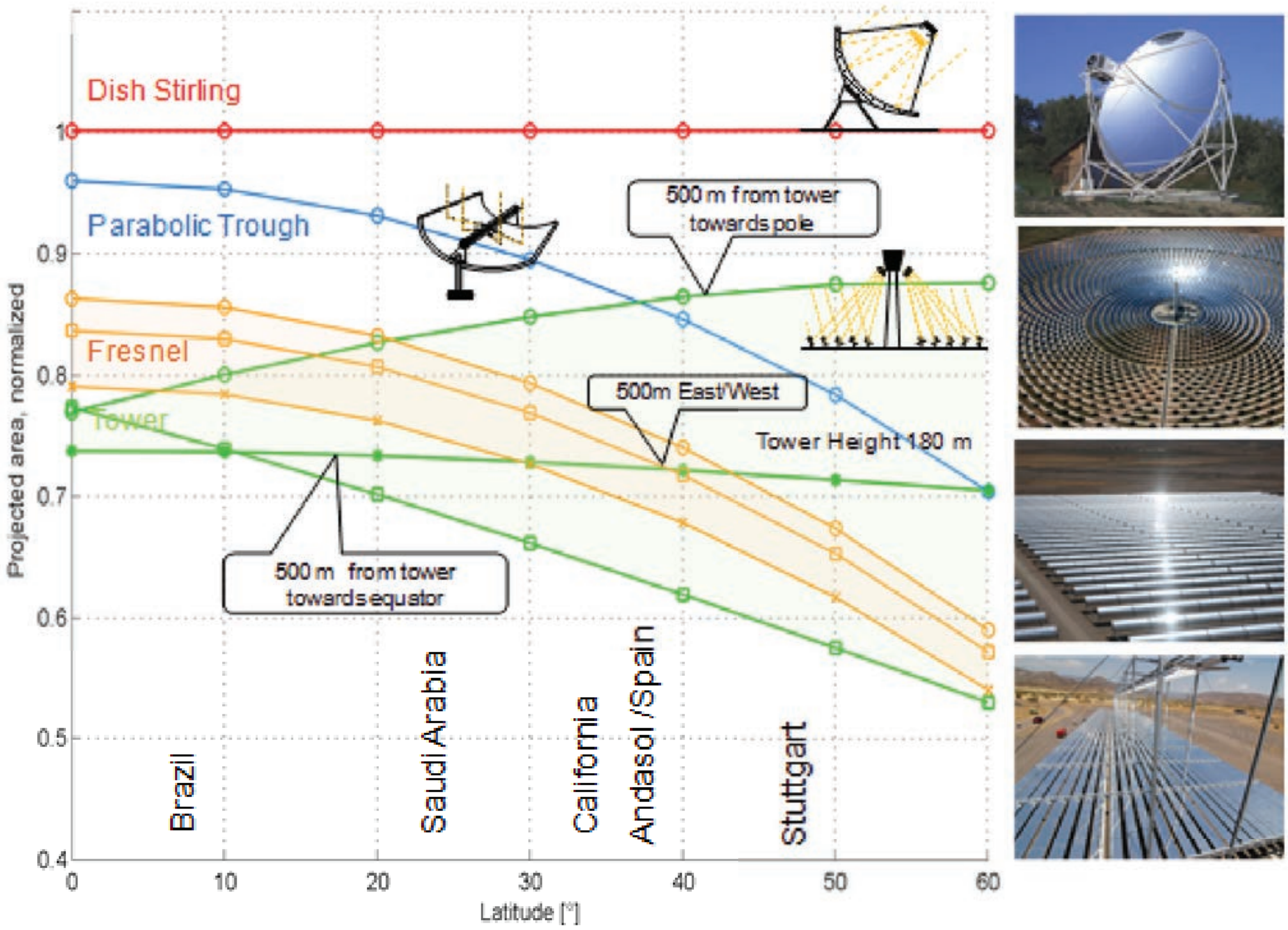


Figure 7: Mean annual effective area ('cosine efficiency') vs. latitude for selected CSP technologies

In contrast to that, parabolic trough collectors oriented in north-south direction are characterized by high cosine efficiency at latitudes relevant for CSP (blue line with circular marker). Interestingly, cosine efficiency is higher than for heliostats, despite the fact that only single axis tracking is being used.

Cosine efficiency is significantly lower for linear Fresnel systems (orange lines); similar to heliostat fields due to the fact that the receiver is fixed (as compared to dish systems and parabolic trough collectors, where the receiver moves with the tracking concentrator.

1.3 PARABOLIC TROUGH FUNCTIONAL PRINCIPLE

A solar parabolic trough collector is an optical device, designed to collect direct solar radiation from the sun and convert it into heat. Solar radiation is concentrated via parabolically shaped reflector panels to a Heat Collecting Element (HCE) located in the optical focal line of the collector. The solar collector is continuously tracking the sun (Fig. 8).

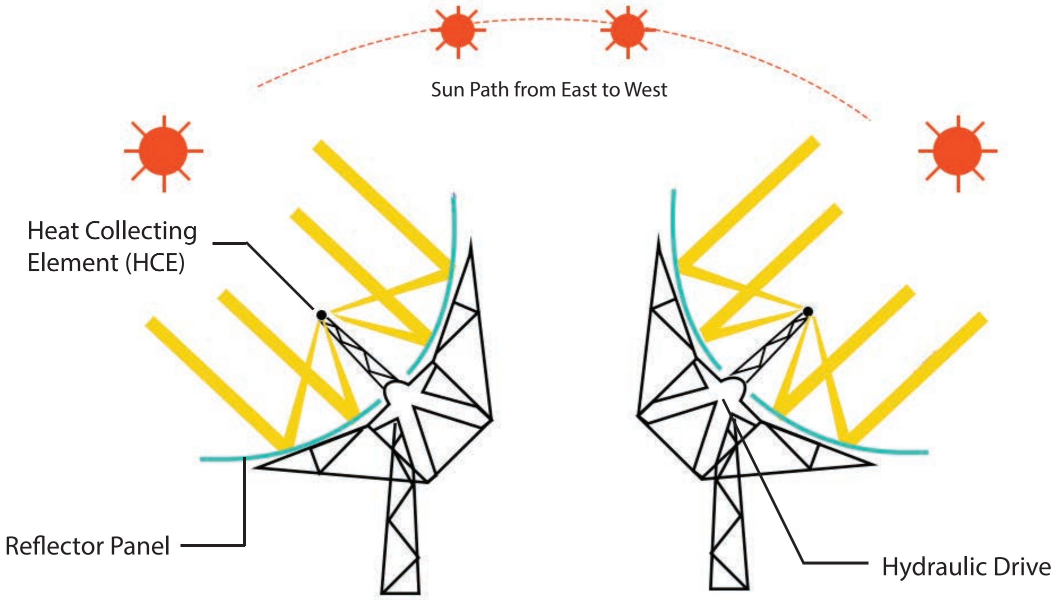


Figure 8: Parabolic trough collector functional principle

A heat transfer fluid is circulated inside the HCEs. It transports the absorbed energy to a conventional power block where heat exchangers are used to generate stream that will drive a steam turbine and a generator where electricity is generated (Fig. 9).

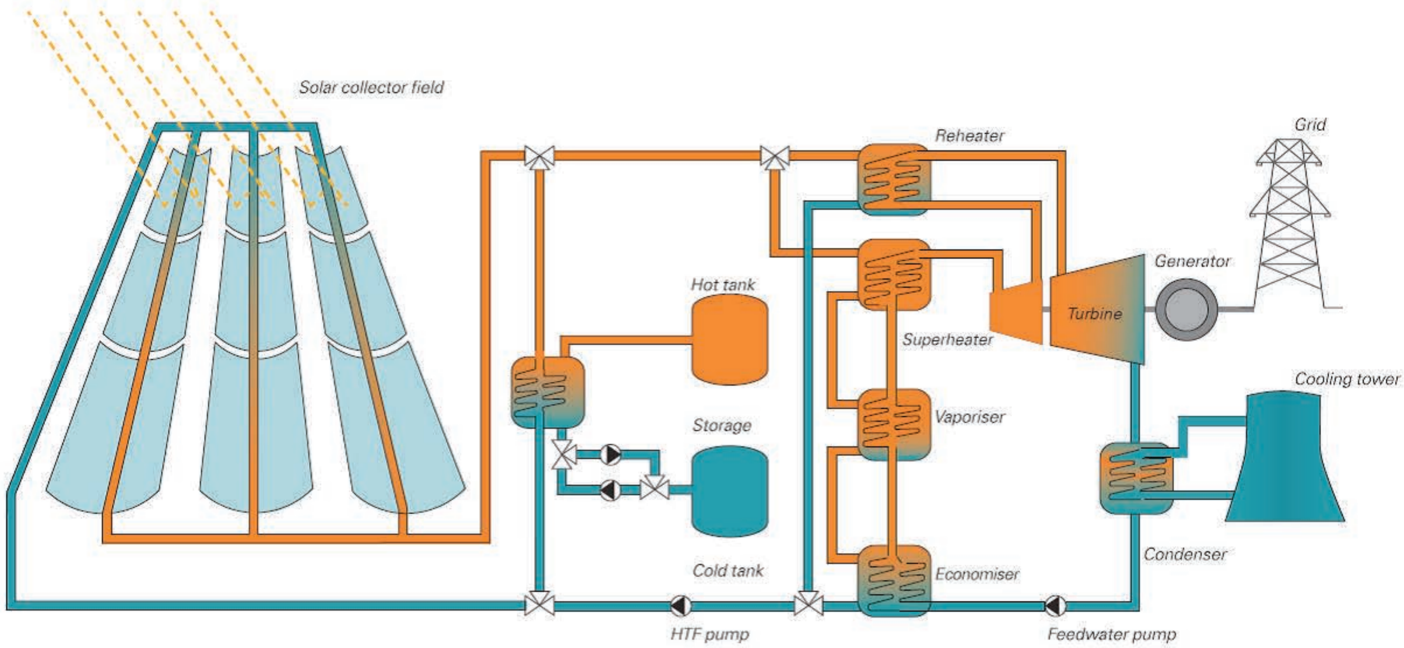


Figure 9:Parabolic trough power plant functional principle [7]

2 OVERVIEW ON PARABOLIC TROUGH COLLECTORS

2.1 INTRODUCTION

The smallest subunit of the collector field is the so-called Solar Collector Element (SCE). A SCE is an eight to 24 meter long collector unit consisting of the supporting structure, parabolically curved reflector panels and the absorber tube (HCE) held in the collectors focal line every four to five meter by so-called HCE posts.

When comparing two collector systems, besides size, the metal supporting structure is the main differentiator. It has the function to carry the reflector panels and absorber tube in their ideal position while the collector is tracking the sun. The stiffness requirements are very high, because any deviation from the ideal parabolic collector shape causes losses in the optical efficiency of the system. Due to the large aperture area and collector length, high wind loads have to be taken by the supporting structure. Specially the wind introduced torsional loads are challenging and are the limiting factor for the total collector length.

Largely, three types of main supporting structures are used: the torque tube, the torque box or a space frame structure. As material mostly steel is used because of its high stiffness and high strength or aluminum because of its low mass. In the last years a couple of new collector designs have been presented that use very different types of alternative supporting structures as for example an inflated flexible membrane tube with an integrated mirrored membrane layer [8] or an area stable composite trough as used by Solarlite [9] or toughtrough [10].

To form a so called solar collector assembly (SCA) a number of SCEs are connected to a torsional stiff unit. At each end of the SCEs the collector is supported by pylons furnished with plain bearings, allowing for rotation along the collector longitudinal axis.

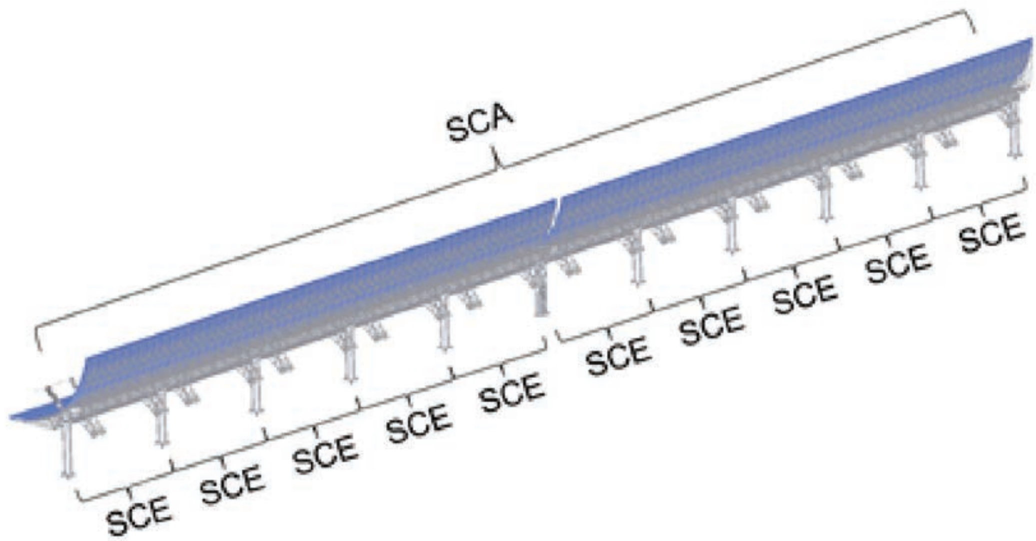


Figure 10: Definitions for parabolic trough collectors: Solar Collector Element (SCE) and Solar Collector Assembly (SCA)

A number of SCAs forms a so called "collector loop". Within the loop all absorbers (HCEs) are connected, the heat transfer fluid flows through all of them, heating up in every collector. To ease the installation of the collecting pipes for the heat transfer fluid, the SCAs are arranged in U-Form with 2 x 300 m length (EuroTrough). At the beginning of each loop the cold heat transfer fluid (HTF) is pumped into the absorber tubes. Between begin and end of the collector loop the HTF is heated up to its maximum operation temperature. The hot fluid is then pumped back to the power block or to the thermal storage systems.

The steel structure of a Solar Collector Element (SCE) is introduced using the EuroTrough as an example. It consists of the following main components:

- The torque box, a rectangular space frame box extending over the SCE length with endplates and torque transfer,
- 28 cantilever arms as supporting structure for the mirror panels, 14 on each side of the torque box and fixed to it,
- 3 HCE supports and associated feet for carrying the HCE tube. HCE supports are bolted to the torque box.
- 28 parabolically curved mirrors (not part of this tender document).
- HCE tube

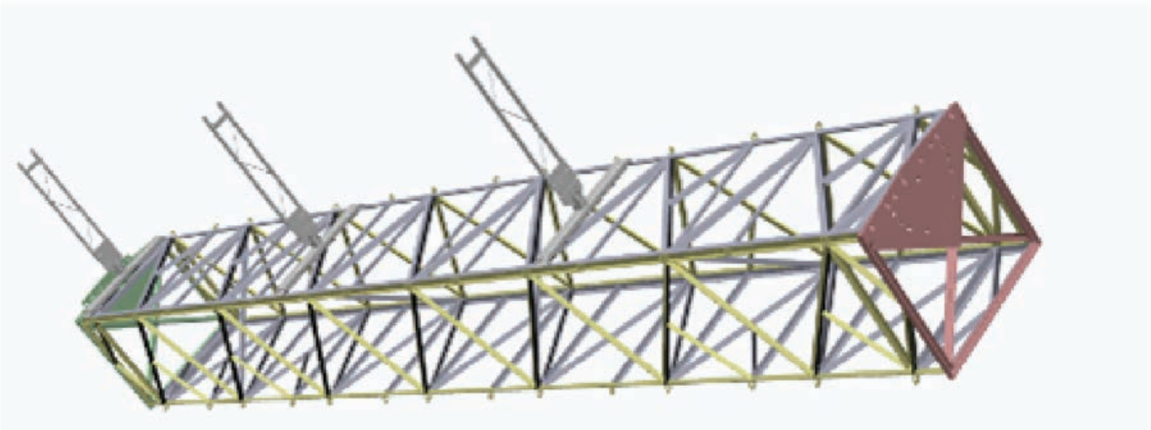


Figure 11: Torque box with HCE supports

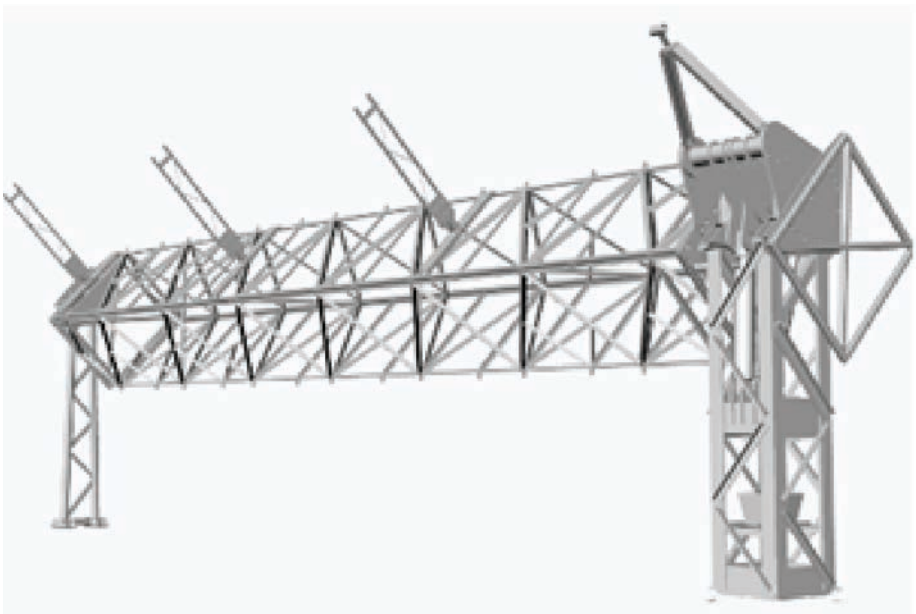


Figure 12: Torque box with drive pylon and middle pylon

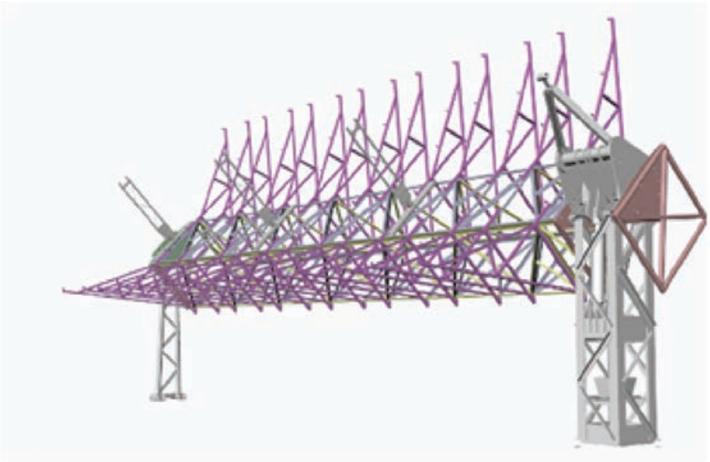


Figure 13: Torque box with cantilever arms

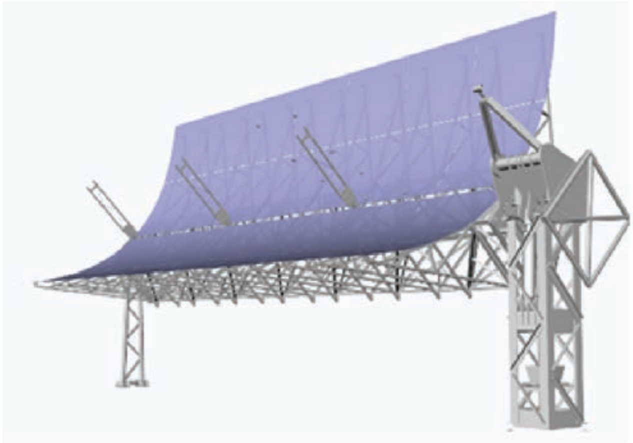


Figure 14: Solar collector element without HCE tube

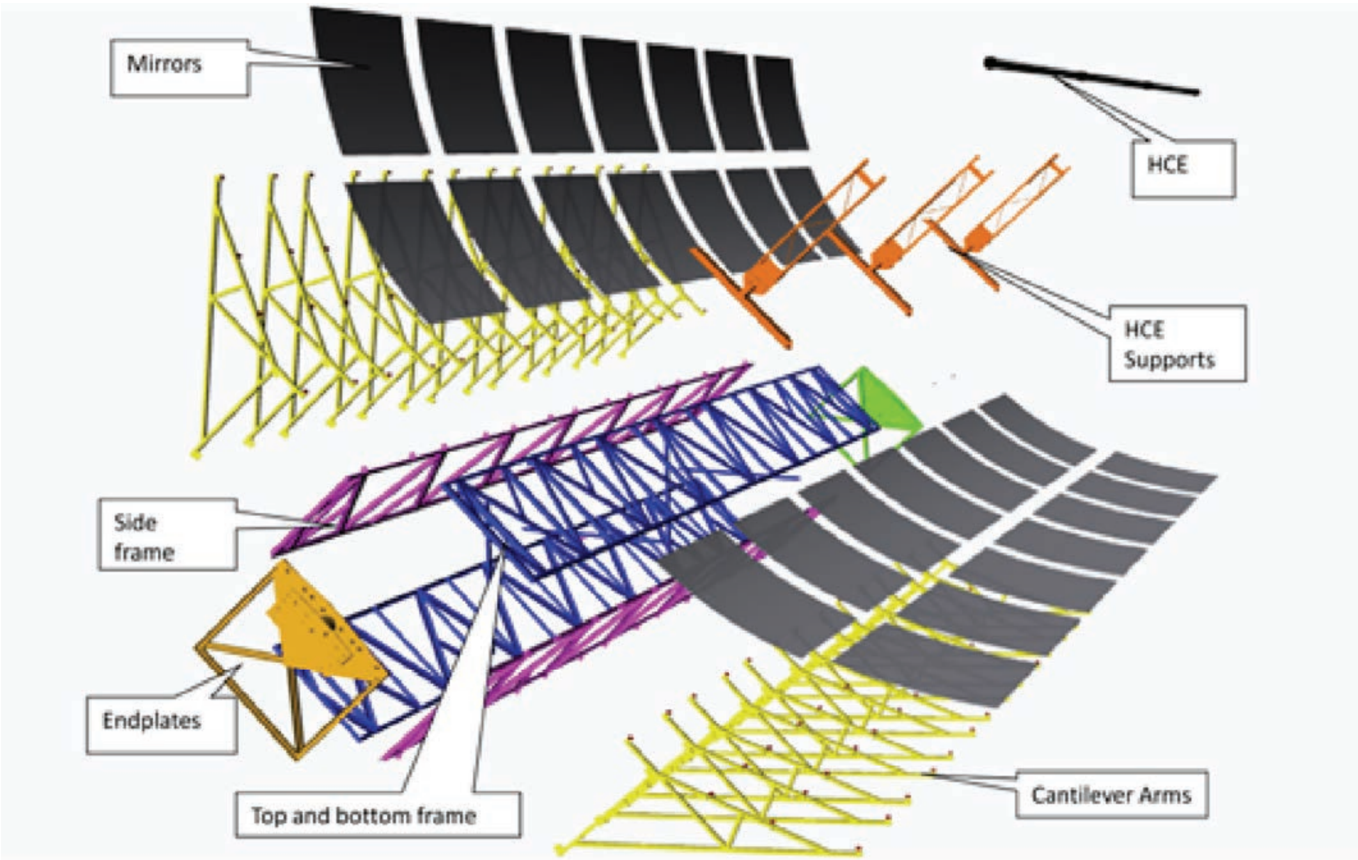


Figure 15: Components of a Solar Collector Element (SCE).

Figure 16: Parabolic Trough collector field with header piping

2.2 THE FIRST COMMERCIAL COLLECTOR GENERATION: LS-1, LS-2 AND LS-3

In the mid-eighties the first SEGS plants were built in the Mojave Desert in California. The parabolic trough collectors used in SEGS 1 – 9 were developed by the US/Israeli company LUZ. Their first trough collector, the LS-1 (Fig. 17), were used in SEGS I and II. Due to the very small size of the LS-1 it was replaced by the next generation, the LS-2 collector that has been used in SEGS II (about 50%) to VII [11]. The LS-2 (like the LS-1) used a torque tube as main structural element (Fig. 18). The glass reflector panels are fixed on cantilevers of lattice framework. The aperture of the LS-2 collector is 5 m.

Figure 17: LS-1 collectors at SEGS II, Daggett (Photo: G. Weinrebe)

SEGS VII to IX were built using the LS-3 collector, the third collector type developed by LUZ. At the LS-3 collector, the developers decided to use a complete new collector structure. The torque tube was replaced by two triangular torque boxes placed between the inner and outer mirror row (Fig. 19). At each collector end a frame connected the two boxes. With these boxes it was possible to increase the span in both directions – aperture and solar element length. The aperture of the LS-3 is 5.76m, the length between the pylons is about 12m. Eight elements were connected to one torsion stiff collector assembly (SCA). The posts supporting the absorber tubes were replaced by two struts.

Figure 18: LUZ LS-2 parabolic trough collector [12]

Figure 19: LUZ LS-3 collector from backside [12]

2.3 CURRENTLY AVAILABLE PARABOLIC TROUGH COLLECTORS

In this chapter an overview on present trough collectors is given. Each relevant trough collector is described shortly. More detailed information for selected collectors is given in the following chapters.

2.3.1 Solargenix (SGX)

The LS-3 design was considered by many to be not really successful. Therefore the designers of the Solargenix collectors SGX 1 and SGX 2, who had partially been involved in the design of the LUZ collectors, decided to select a different structural approach for their new collectors. They also selected the smaller RP-2 panel dimensions (as compared to the LS-3's RP-3) for their new developments, because this design and dimensions had worked well.

The SGX 1 is used at the 1 MW Saguaro plant in Arizona. The SGX 2 is an improved space frame design and a natural evolution from the SGX 1. It was developed by Solargenix Energy and NREL. The space frame is made from extruded aluminum in order to be very light and to require very few fasteners. The SGX2 collector is easy to assemble without the need of any complicated or expensive fabrication jig [13]. Aperture width of the SGX-2 is 5m (mirrors: RP-2, total SCA length: 100 m.

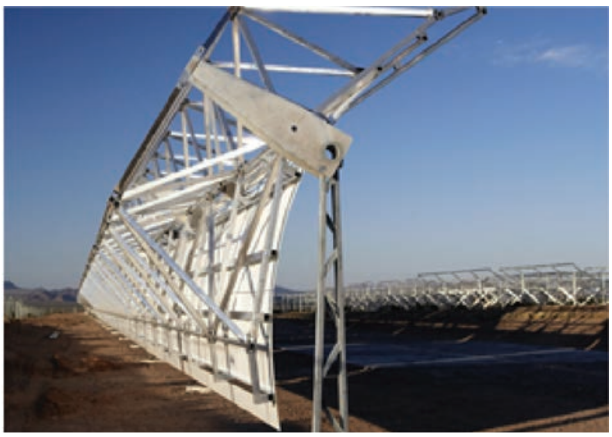


Figure 20: Solargenix / Gossamer Spaceframes / Acciona aluminum space frame parabolic trough collector at Nevada Solar One site (south of Las Vegas, NV) [12]

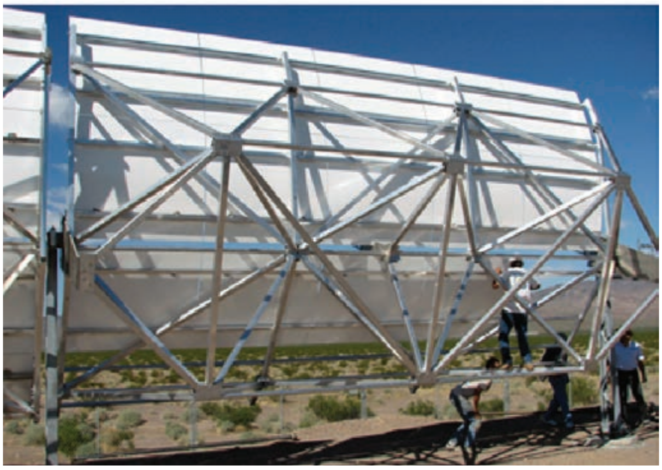


Figure 21: Solargenix Collector SGX-2 deployed at Nevada Solar One [12]

2.3.2 EuroTrough

After years without progress in collector development, the EuroTrough collector was developed by a group of European companies (cf.1.1). In the year 2000, a first prototype was built at the Plataforma Solar de Almeria, the European test and research facility in Southern Spain.

At this time, the industry was not ready to deliver larger absorber tubes or reflector panels than used by the LUZ collectors, therefore the outer dimensions of the LS-3 collector had to be chosen for the EuroTrough, too. To increase stiffness, a central rectangular torque box is used instead of two small triangular boxes (LS-3). The box has outer dimensions of about 1.5 x 1.4 meter and a length of twelve meters. It consists of four lattice framework ladders connected at the chords. At both sides of the box, 14 trussed cantilever arms of thin-walled hollow sections act as support elements for the glass reflector panels.

The resulting high torsional stiffness allows to increase the number of collector elements per drive from eight, as used with the LS-3, to twelve. That step made it possible to build 150-meter long collectors which meet the high optical demands to focus the light that is incident on the aperture of 5.76 m onto an absorber tube having an outer diameter of 70 millimeters [14].

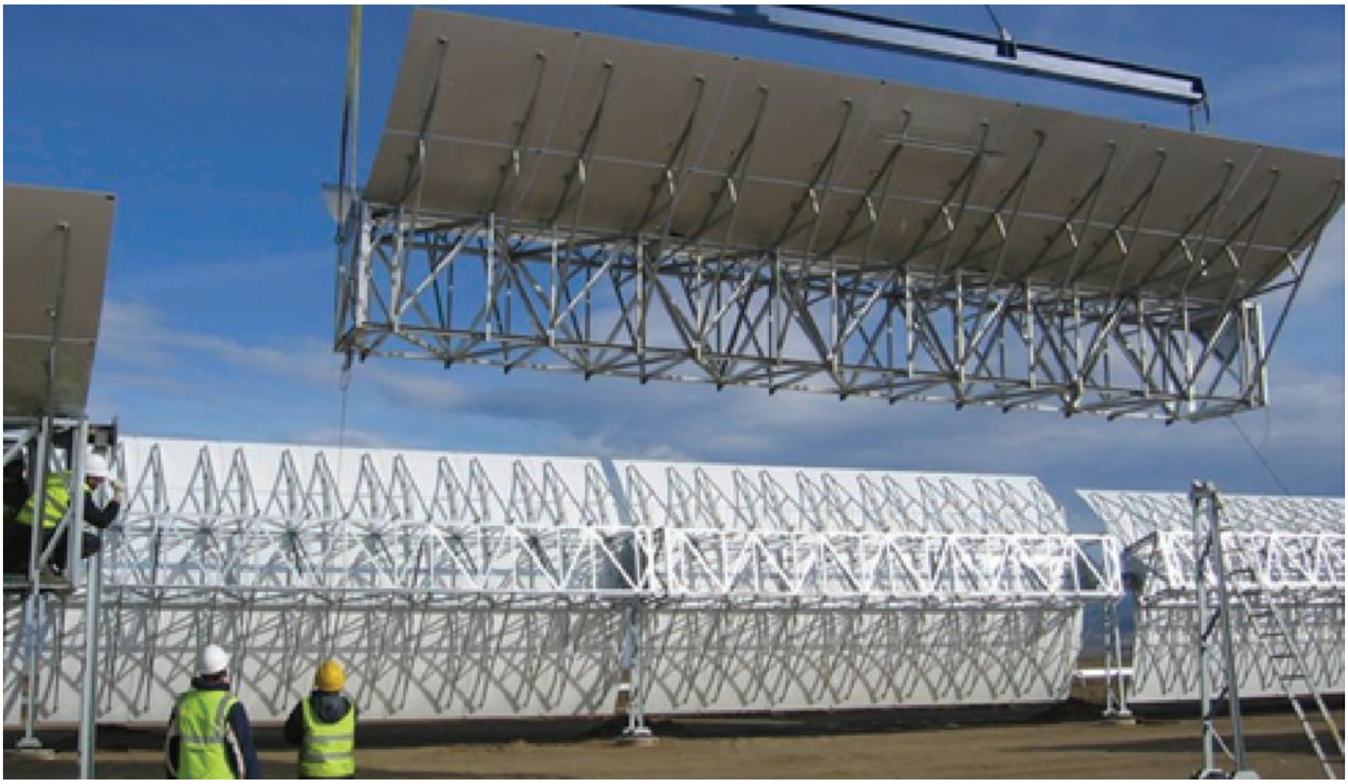


Figure 22: EuroTrough SCE installation in the Andasol solar field, Spain

Encouraged by the high optical quality of the prototype and the good economical perspective that was expected for the future development of solar power generation, it was decided to start the preparation for the first commercial 50-MW plant in Spain. To reduce the risk in the transition from prototype stage to commercial solar field, an additional test loop with an aperture area of 4360m^2 was integrated into a commercially operated solar thermal plant (SEGS V in California).

With the newly introduced feed-in-tariff in Spain, the erection of Andasol 1, one of three very similar 50 MW plants, started in 2008. This was the real start of the global renaissance of solar thermal power generation.

Shortly after the development of the Euro Trough a number of other parabolic trough collectors were developed. On one hand, these were collectors very similar to the EuroTrough such as the ASTRO collector by Abengoa or the scaled LS-2 collector by SENER, on the other hand they had completely new structures like the space frame of the SGX collector by Solargenix (later acquired by Acciona).

ASTRO

The ASTRO collector is very similar to the Euro Trough. One of the very few changes is the reduction of cantilever arms and the use of longitudinal purlins to support the reflector panels.

2.3.3 SENERtrough

The SENERtrough uses a torque tube instead of a torque box and follows the principles of the LS-2 collector. The torque tube center is not in the collector's rotation axis. At each pylon, a smaller tube ('torque transfer tube') is positioned in the center of gravity. This tube is supported on sleeve bearings.

The reflector panel and receiver dimensions of the LS-3 are used, the collector length equals the 150 meters of the EuroTrough.

Instead of trussed cantilevers as used in the LS-2 collector, stamped arms are used to support the reflector panels.

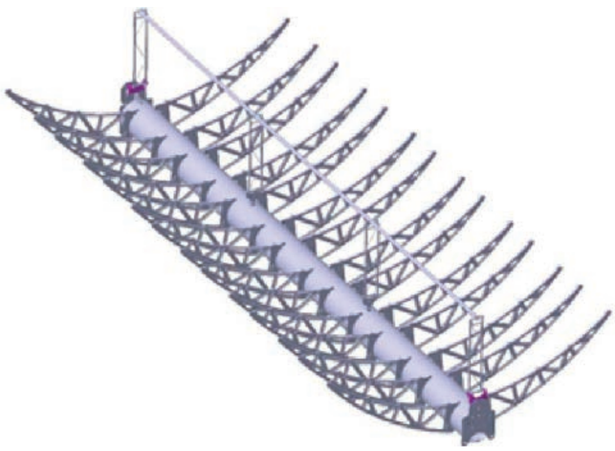


Figure 23: Torque Tube of the Senertrough

The Sener Trough is the most commonly built collector today (2013).

2.3.4 ENEA Collector

ENEA, the Italian National Agency for New Technologies, Energy and Sustainable Economic Development, together with industrial partners, designed the first collector that uses molten salt as heat transfer fluid.

Figure 24: Enea parabolic trough collector [15]

The ENEA collector utilizes a torque tube as main structure element. The cantilever arms are made of sheet metal and follow the parabola. As reflector panels a special aluminum honeycomb facet with thin glass mirrors is used. These stiff panels can be produced in very large sizes so that the assembly process of the facets is simplified. The aperture width of 5.76 meters is similar to the LS-3 dimensions. Total collector length is 100 meters.

Since 2010 the ENEA collector is used in a 5 MW demonstration power plant in Sicily.

2.4 RECENT COLLECTOR DEVELOPMENTS - INTRODUCTION

Encouraged by the remarkable success of the previously presented collectors, more collectors have been developed in the last five years. Due to the tremendous growth of the entire CSP industry suddenly much better options were available. Through new mirror products, the old LS-3 geometry - that limited the aperture size at that time - could be abandoned.

Absorber tubes having larger outside diameters allowed to scale concentrators without changing the concentration ratio. Also pressure losses could be reduced by increasing the diameter.

Moreover, new markets were opened, in which the size of the power plants were not capped to 50 MW as in Spain. The longer collectors allow for a better field layout, so that the costs for piping can be substantially reduced (see chapter 4.4).

With the new products and new boundary conditions usually larger collectors were developed. Most collectors are based on previously used systems (e.g. the UltimateTrough is based on the EuroTrough, the SENERtrough-2 collector on the SENERtrough-1), others use entirely new structures (Solarlite, toughtrough). These collectors are introduced in the following sections.

2.4.1 HelioTrough (HT)

Like the LS-2 collector, the HelioTrough uses a torque tube as main structural member. As an innovation, the tube has a constant stiffness along the whole collector length and consequently acts as continuous beam. This allows for a wider span, as the deflection from dead load is reduced drastically by the continuous beam effect. All other collector structures built before have a stiffness gap between the SCEs (at the torque transfer tube).

Aperture width is 6.78 m, SCE length is 19 m. Total SCA length is 191 m. The mirrors are carried by trussed cantilever arms pinned to the torque tube. In order to reduce end losses between the SCEs the gaps between the mirrors were reduced to an absolute minimum.

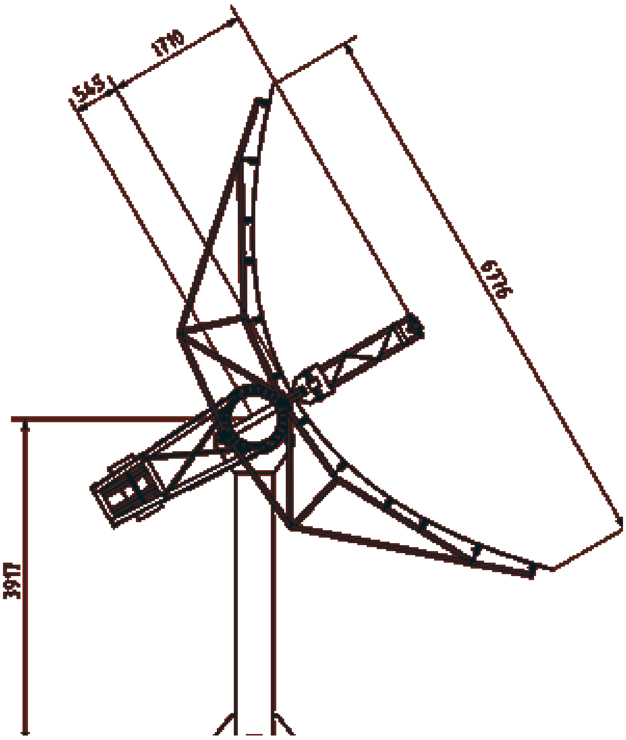


Figure 25: HelioTrough collector main dimensions collector [16]

The HelioTrough design has the following design targets and characteristics[16]:

- Reduced number of parts (mirrors, HCEs, steel parts, drives, swivel joints, control systems etc.)
- Reduction of assembly and alignment costs
- Reduction of maintenance costs
- Increased lifetime
- Center of gravity below mirror surface in the center of the torque tube
- First gapless SCA (no mirror gap between individual SCEs)
- Improved efficiency due to reduced heat losses
- Better usage of HCEs
- Less space consumption
- Assembly and mounting of mirrors: patented 3D-tolerance adjustment
- Mirrors are placed on an accurate jig,
- Mirrors in a perfectly shaped parabola
- SCE-frame is lowered on the jig
- Anchor rods are surrounded by the hollow shape of the pods
- Pods are filled with glue, while the mirrors stay in the ideal position

• Improved optical efficiency due to perfectly shaped parabola
• Less mirror breakage by tension free connection
• New bearing concept
• Support roller with maintenance free bearing
• very low friction leads to low torsion and high performance
• New cross over pipe design
• No pylons (free access for maintenance equipment)
• Less pressure losses in comparison with a horseshoe bend

Figure 26: HelioTrough collector

These special design features have been patented by Flagsol GmbH & schlaich bergermann und partner.

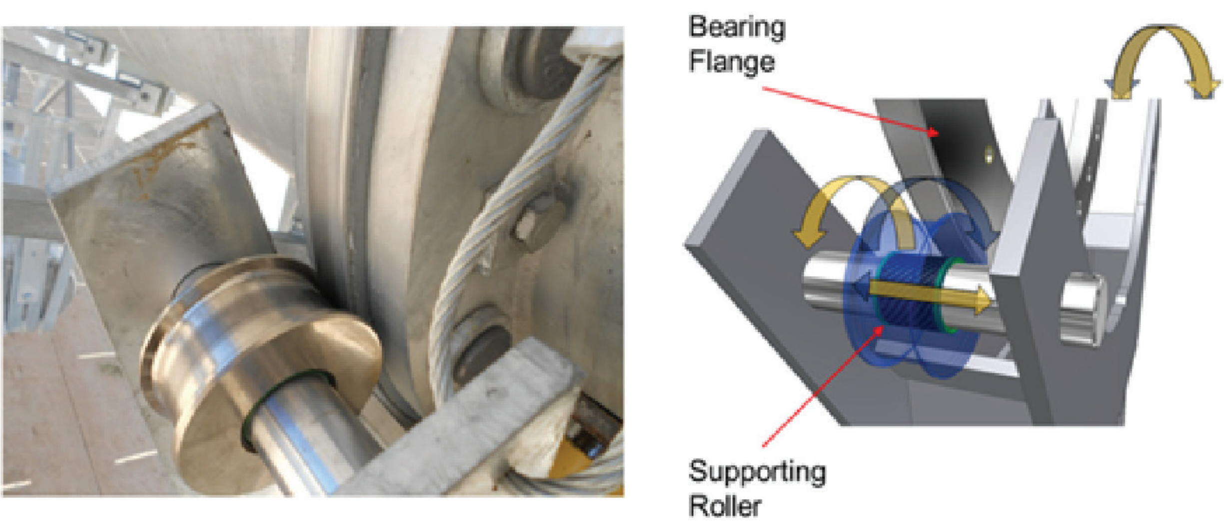


Figure 27: HelioTrough collector bearing at middle pylon [17]

2.4.2 Ultimate Trough (UT)

The Ultimate Trough is mainly based on the EuroTrough. As main supporting system, a trussed torque box is used. Due to the high bending stiffness of this structure, the span could be increased to 24.5 meters. Also an aperture of 7.51 m could be realized. Total SCA length is 246 m.

As the HelioTrough, also the UlimateTrough has a continuous mirror surface. The glass mirrors are designed for the current maximum dimensions that can be manufactured. Between the inner and outer mirror there is an offset, which moves the center of gravity of the collector in the desired direction, and provides a wind pressure relief gap between the front and back of the reflector panels, thus reducing wind loads significantly.

Figure 28: UltimateTrough collector during transport on site

The UltimateTrough features a steel structure with torque box design, characterized by an extremely high torque and bending stiffness and an economic use of material. It also results in a lower wind resistance coefficient compared to a torque tube design.

The innovative joining method "clinching" is used for torque box assembly, saving more than 50% of bolts and nuts in the solar field while allowing the tension free assembly of the box frames despite high allowable variance.

A wind release gap between the inner and outer mirror reduces wind loads up to 30%; there are no mirror gaps across the pylons. This could be realized because as the center of gravity and rotation is below the mirror surface.

The UltimateTrough also features a new and innovative joining method for the steel structure/ mirror connection, allowing high variance and thereby a tension free mirror junction.

A cost effective and precise patented alignment procedure for the assembly of collector elements in the field is used.

The UltimateTrough is currently the world largest collector element (24 m x 7.5 m) respectively collector assembly (247 m x 7.5 m), showing a peek optical efficiency of 82.7%. This efficiency number includes an intercept factor of 99.2%, taking into consideration sun shape, alignment and tracking error [18].

2.4.3 SENERtrough-2

The SENERtrough-2 collector is a scaled version of the SENERtrough-1 collector. The aperture width, collector element length and focal length have been increased. The drive pylon structure is based on a vertical pipe.

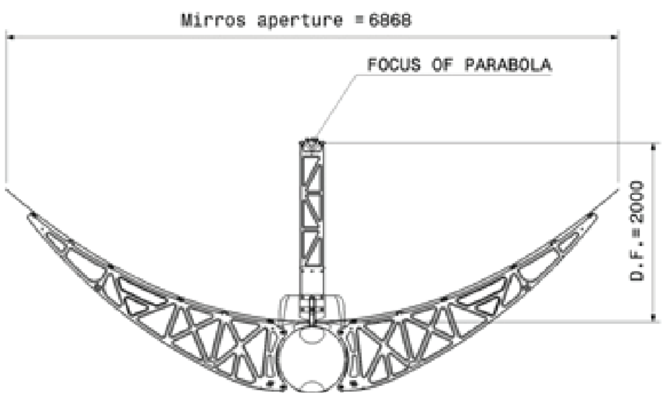


Figure 29: Sener_2 collector (shown without pylons and foundations)

Figure 30: Sener_2 collector (left) and Sener 1 collector (right)

2.4.4 SkyTrough

The SkyTrough is developed by the US company SkyFuel [19]. Like the SGX collector, the SkyTrough utilizes an aluminum space frame. With 6 m aperture width and a total SCA length of 115 m the SkyTrough is larger than the SGX-2. Differing from all collectors introduced above, the SkyTrough uses a reflective polymer mirror film attached on an aluminum sheet instead of monolithic glass reflector panels.

Figure 31: SkyFuel collector back structure and metal reflector sheets [20]

Figure 32: Detail of SkyFuel collector structure

2.4.5 Large Aperture Trough (LAT) 73

The LAT is a development of 3M [21], [22] and Gossamer Space Frames [23]. Like for the SkyFuel collector, an aluminum space frame and a reflective polymer film is used. Aperture width of the LAT 73 is 7.3 m; total SCA length is 192m.

Figure 33: Large Aperture Trough (LAT) 73 [23]

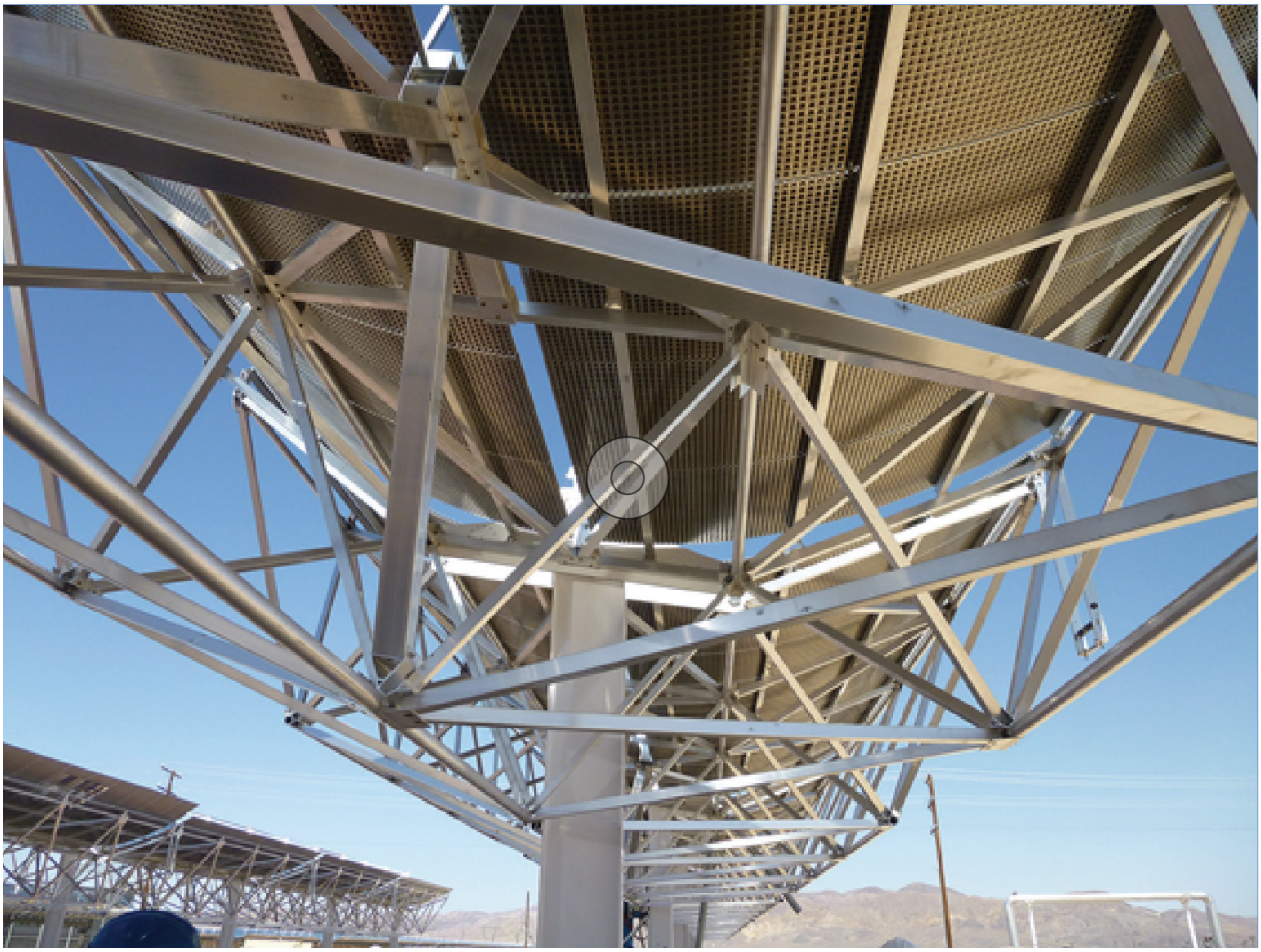


Figure 34: Large Aperture Trough (Lat) 73 structural details

Recently, Gossamer Space Frames and 3M are developing a similar collector with an even slightly larger aperture width.

2.4.6 Abengoa E2

Abengoa's current collector, the Eucumsa (E2), is a steel space frame collector. The aperture of the LS-3 and a SCA length of 125 m is used. In contrast to the SkyTrough and the LAT, monolithic glass reflector panels are connected to the steel structure via purlins.

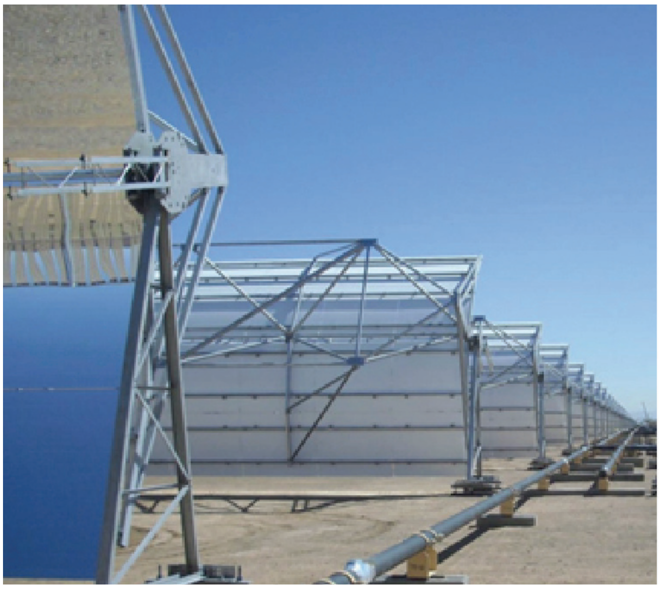


Figure 35: Abengoa E2 collector [24]

Figure 36: Abengoa E2 collector, structural details

2.4.7 Airlight

The Swiss company Airlight [8] developed a large area collector system (Fig. 38) that uses fiber reinforced concrete and inflated polymer membrane as structural material. As reflective layer a polymer film is glued onto a parabolically shape membrane. The aperture width of the structure is 9.7m.

Instead of synthetic oil or molten salt air is used as heat transfer fluid.

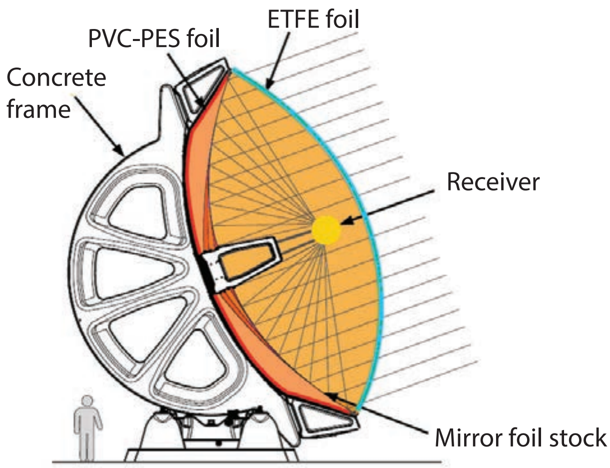


Figure. 37: Airlight trough principle [25]

Figure 38: Parabolic trough collectors using concrete as main structural material [25]

2.5 CHARACTERIZATION OF PARABOLIC TROUGH COLLECTORS

In Fig. 39, a genealogy of parabolic trough collectors is shown. It illustrates the different development lines.

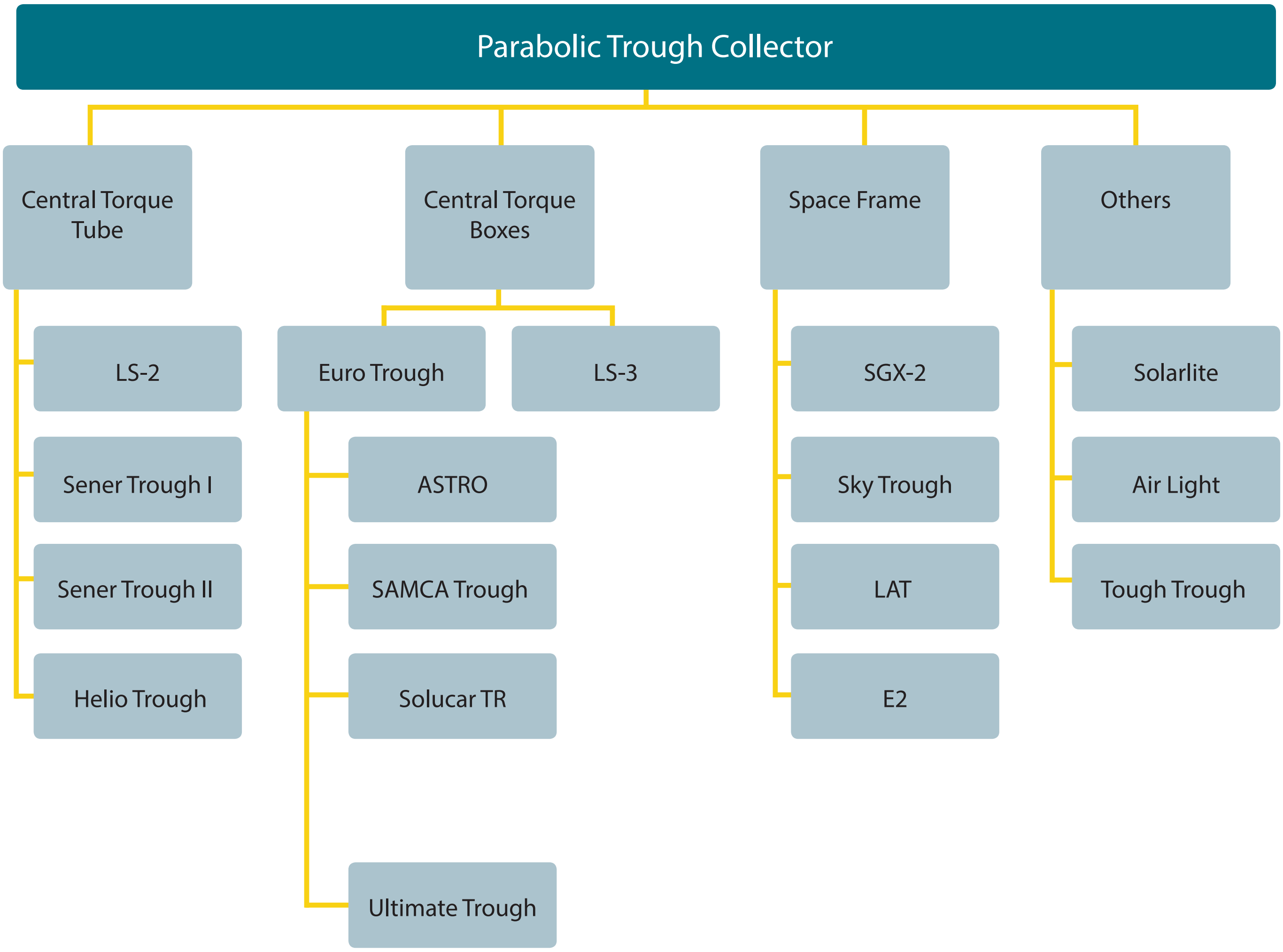


Figure 39: Genealogy of parabolic trough collectors

2.6 TYPICAL PARAMETERS FOR SELECTED COLLECTOR TYPES

This chapter gives an indication on typical parameters of selected collector types.

2.6.1 Collector Dimensions

First, main collector and receiver dimensions are discussed. The first generations (LS-1/LS-2) were relatively small collectors. Aperture width was about 5m and the collector length (SCA length) roughly 50m.

With the next generation, the size of SCEs increased. The following boundary conditions led to the LS-3 size: float glass width, max concentration ratio and available HCE dimensions. The collector length has been largely determined by collector stiffness. High collector stiffness is required to achieve the desired optical quality and for load capacity reasons. The LS-3 has an aperture width of 5.76 m, the length between the pylons is about 12 m. Eight elements were connected to one torsion stiff collector assembly (SCA) with a total length of about 100 m.

Using the LS-3mirror geometry, the EuroTrough was developed in the nineties. By that time, no other mirror or receiver dimensions were available. Due to a significantly stiffer support structure, longer collectors can be built, which still possess a higher optical efficiency. Beside the EuroTrough, a variety of other collectors developed later (Sener 1, ASTRO, etc.) are using the LS-3 mirror and receiver geometry.

In recent years new types of collectors were designed. The aperture as well as the length of the collectors has usually been increased. Respective collector and receiver dimensions are listed in Table 1.

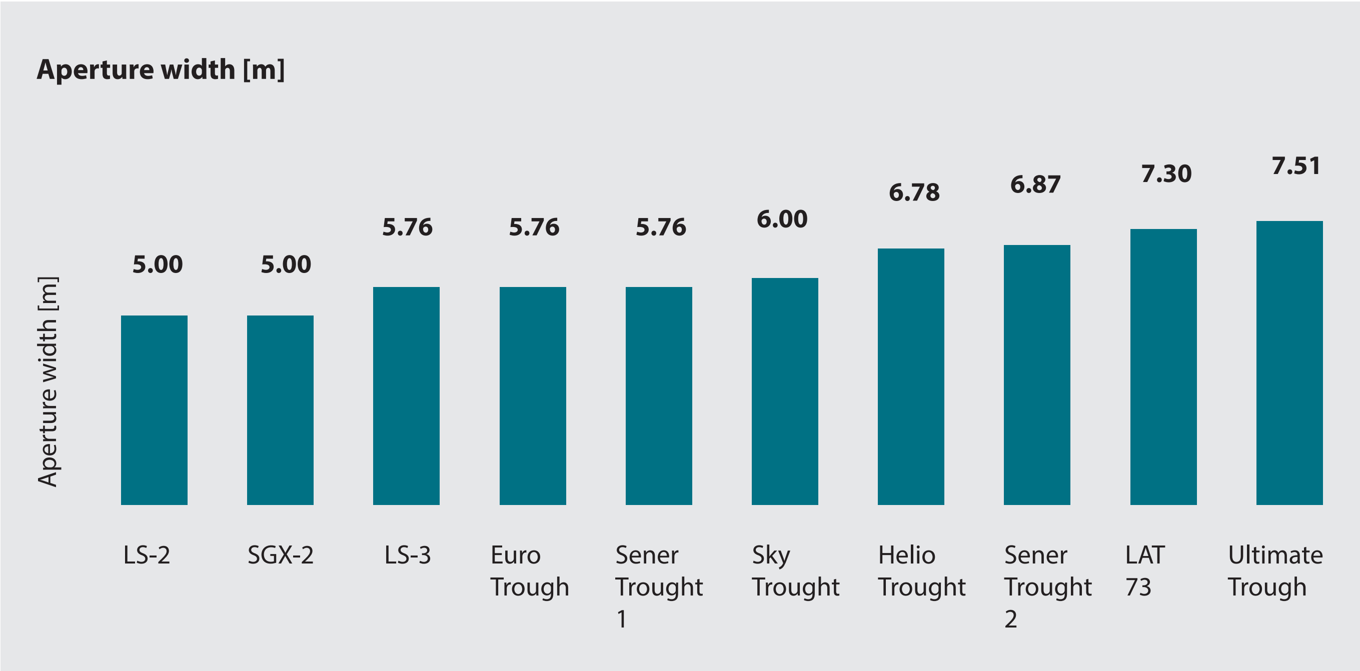


Figure 40: Increasing aperture in the course of parabolic trough collector development

	Aperture width [m]	SCE Length [m]	SCE per SCA [-]	HCE Diameter / Aperture [mm]	Net Aperture Area / SCA [m²]
LS-2	5.00	7.8	6	70	235
SGX-2	5.00	8*	12*	70	470
LS-3	5.76	12	8	70	545
EuroTrough	5.76	12	12	70	818
Sener Trough 1	5.76	12	12	70	818
SkyTrough	6.00	14	8	80	656
HelioTrough	6.78	19	10	89	1263
SENERtrough-2	6.87	13.2	12	80	1048
LAT 73	7.3	12	16	70	1392
UltimateTrough	7.51	24.5	10	94 (70)	1716
Airlight	9.7	17.6	12	140	2053

Table 1: Main dimensions of selected parabolic trough collectors

2.6.2 Concentration Ratio

Radiation concentration is necessary if higher temperatures than those generated by flat-plate collectors are required. The concentration of solar radiation is described by the concentration ratio. It can be defined according to two different methods:

- On the one hand, concentration ratio C can be determined solely geometrically (C_{geom}), describing the ratio of the solar aperture surface Aap to the absorber surface A_{abs} (Equation (1)); explanations within this chapter are based on this definition. Thus, the concentration ratio of a typical parabolic through collector of an aperture width of 5.76 m and an absorber tube diameter of 70 mm amounts to approximately 26. With regard to parabolic through collectors, sometimes the ratio of aperture width to absorber tube diameter (projected absorber area) is referred to as concentration ratio; this quantity differs from the concentration ratio defined by Equation (1) by factor π.

$$C = C_{geom} = \frac{A_{ap}}{A_{abs}} = \frac{A_{ap}}{\pi d_{abs}} \qquad (1)$$

- On the other hand, the concentration ratio C can be defined as the ratio of the radiation flux density G_{ap} at the aperture level and the corresponding value G_{abs} of the absorber (C_{flux}, Equation (2)). However, this definition is only mentioned here to complete the picture.

$$C = C_{flux} = \frac{G_{ap}}{G_{abs}} \qquad (2)$$

In practice, the achievable concentration ratio is considerably smaller than the theoretical maximum. This is due to the following aspects:

- Tracking errors, geometric deflections as well as imperfect orientation of the receiver
- The applied mirrors are imperfect and expand the reflected beam
- Atmospheric scattering expands the efficient aperture angle of the sun far beyond the ideal geometric value of the acceptance semi-angle of approximately 4.7 mrad

Radiation concentration aims at increasing the possible absorber temperature and consequently the exergy of the concentrated heat. In addition, absorber diameter/surface can be reduced, thus reducing thermal losses due to radiation, convection and heat conduction. In case of absorbers of parabolic through collectors, this is achieved by evacuated tubes and by an absorber coating with a low emission coefficient within the relevant wavelength range. Fig. 41 shows the impact of the concentration ratio on the collector efficiency ηColl over the absorber temperature θabs for a typical emission coefficients ε of the absorber (εabs= 0.08).

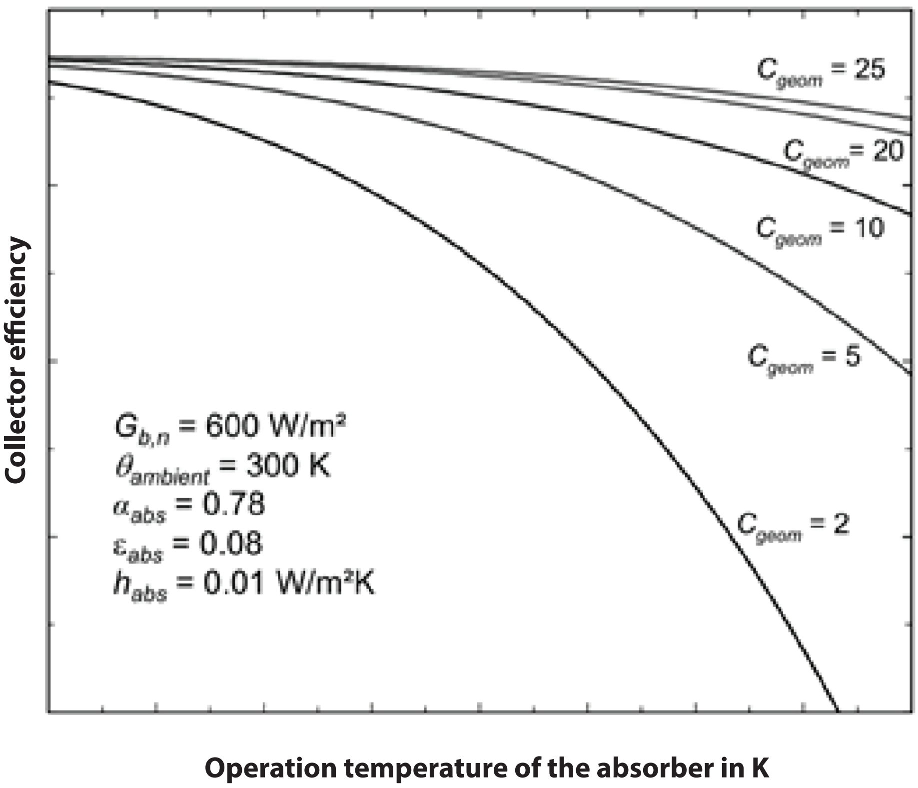


Figure 41: Collector efficiency vs. operation temperature

For the sake of simplicity a constant intercept factor (i.e. ratio of incident to reflected radiation) of 0.96 has been assumed; $G_{b,n}$ describes the direct normal radiation; α_{abs} is the absorption coefficient of the absorber; h_{abs} is the thermal loss coefficient of the absorber.

Hence, the absorber tube must have a sufficient diameter to permit a high intercept factor. The intercept factor is the ratio of the total reflected radiation to the reflected radiation that hits the absorber surface. On the other hand, the absorber diameter should not be too big in order to keep the thermal losses low. An absorber tube with a big diameter has a large surface area per meter and loses therefore more heat than an absorber tube with a smaller diameter.

The optimal concentration ratio is therefore depending on the concentrator slope errors, focal length, opening angle, sun shape, the operation temperature and other parameters (pressure losses, etc.). The Ultimate Trough is available as synthetic oil and as molten salt collector. Hence, the operation temperature is different (also pressure losses), the slope deviations and most of the other parameters stay untouched. However, the optimum absorber tube diameter for the molten salt version is 70 mm, where a 94 mm HCE tube is utilized by the synthetic oil version.

	C_{geom}	C_{geom} (projected)
LS2	23	71
SGX-2	23	71
LS3	26	82
ET	26	82
Sener Trough 1	26	82
HT	24	76
Sener Trough 2	27	86
Sky Trough	24	75
LAT 73	33	104
UT	27 / 34	84 / 107
Airlight	22	70

Table 2: Concentration ratios of selected parabolic trough collectors

2.6.3 Nominal thermal power and nominal efficiency at design conditions

As solar energy changes with the time of the year and fluctuates due to cloudiness, a special set of conditions is specified to define the nominal electric power output of a solar power plant. These conditions are called the *design point*.

The conditions are chosen to reflect a "typical" operational situation where the power plant is assumed to operate at nominal conditions.

Common design point conditions are:

- Direct normal irradiance (often 850 W/m^2)
- Time and date (often noon at equinox)
- Realistic optical efficiency of the parabolic trough at that time and date
- Temperature, pressure and relative humidity of ambient air

These conditions are determined to calculate the power plant's "efficiency at design point".

Another design parameter of solar power plants is the solar multiple (SM). It is defined as the ratio of solar field thermal output at design point conditions to thermal input needed by the power block to run the turbine at full capacity and produce the nominal electricity output:

$$SM = \frac{Q_{thermal,solar\ field,nominal}}{Q_{thermal,power\ block,nominal}} \quad (3)$$

The solar multiple makes it possible to represent the solar field aperture area as a multiple of power block rated capacity. A solar multiple of one (SM=1) represents the solar field aperture area that, when exposed to solar radiation equal to the design radiation value (*irradiation at design*), generates the quantity of thermal energy required to drive the power block at its rated capacity (*design gross output*), accounting for thermal and optical losses [26].

Because at any given location the number of hours in a year that the actual solar resource is equal to the design radiation value is likely to be small, a solar field with SM=1 will rarely drive the power block at its rated capacity. Increasing the solar multiple (SM>1) results in a solar field that operates at its design point for more hours of the year and generates more electricity. This allows the operation of the power block at its nominal output, even if the actual DNI is below the DNI at the design point [26].

A solar field with a SM > 1.5 is necessary for reasonable use of a thermal storage.

Solar fields with SM > 1 will provide more thermal power than the power block can handle at some times of the year, but will also ensure a good degree of capacity utilization for the turbine. On times with too much thermal power, some of it is dumped by intentionally defocusing an appropriate number of collectors.

As always, a holistic approach is necessary to find the ideal trade-off.

Solar power plants never operate at rated capacity over a full year, e.g., due to maintenance. The plant may also run, but with reduced efficiency, if the solar field does not provide enough thermal power to drive the turbine at its design point.

The capacity factor indicates the annual degree of capacity utilization for the power plant. It is defined as the ratio of the actual output of the power plant over a period of time and its output if it had operated at full nameplate capacity the entire time:

$$Capacity\ factor = \frac{Q_{electric,annual,produced}}{Q_{electric,annual,nominal}} \quad (4)$$

The capacity factor is used to estimate the overall operating reliability; it needs to be considered in deciding whether a solar energy project should be developed.

2.6.4 Solar incident angle and optical efficiency

Direct radiation from the sun does usually not come in along the collector's normal, but with a certain angle of incidence θ (Fig. 42).

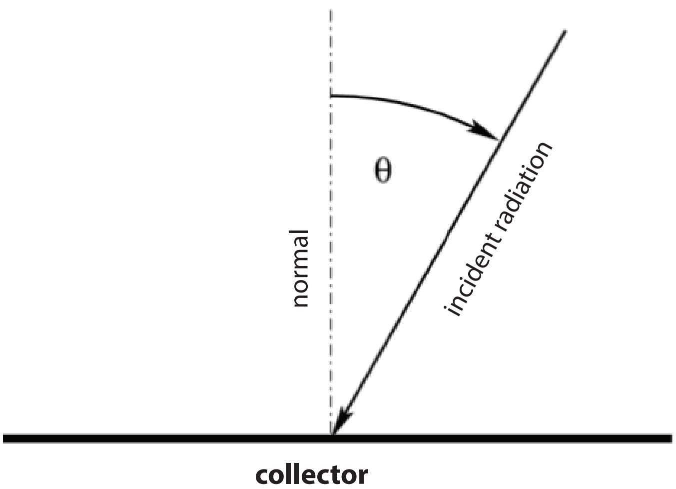


Figure 42: Angle of Incidence

The effective reflective area of a concentrator is defined as the area being 'visible' to the sun. It depends on the incident angle of solar radiation.

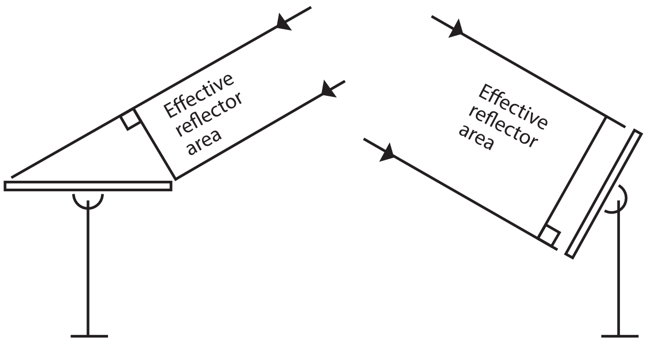


Figure 43: Effective reflector area [27]

The effective reflective area A_θ can be calculated from the total aperture area:

$$A_\theta = A_{total} * \cos(\theta) \quad (5)$$

The term cos(θ) is usually referred to as cosine *efficiency* η_{cos}

Fig. 45 shows how the cosine efficiency effects parabolic trough collectors. The images show the collector as it is seen from the sun at different incident angles. The effective reflective area decreases with increasing incident angle; solar irradiance is "diluted".

Cosine efficiency η_{cos} is not the only factor depending on the incident angle that decreases the overall optical efficiency of the collector.

The *incident angle modifier* K_θ is a derate factor that accounts e.g. for collector aperture foreshortening ("end losses"), unlit HCE due to mirror gaps, HCE post shading, glass envelope transmittance, reflectance and absorptance, selective mirror reflectance or precision during the assembly. It is derived using optical and thermal measurements $\eta_{opt,\theta}$ at different incident angles and comparing them to the efficiency η_(opt,0) at θ=0°:

$$K(\theta) = \frac{\eta_{opt,\theta}}{\eta_{opt,0}} \quad (6)$$

($\eta_{opt,\theta}$ does not include $\eta_{cos,\theta}$)

Then a polynomial fit is used to calculate three coefficients a1, a2, a3 so that K_θ can be calculated using the following empirical equation:

$$K(\theta) = a_0 + a_1 \frac{\theta}{\cos\theta} + a_2 \frac{\theta^2}{\cos\theta} \qquad (7)$$

An overall incident angle dependent efficiency η_θ including $\eta_{cos\theta}$ is calculated as

$$\eta_\theta = \eta_{cos,\theta} * K(\theta) \qquad (8)$$

The coefficients a1, a2, a3 can be used to compare different collector types, however they are usually not available to the public.

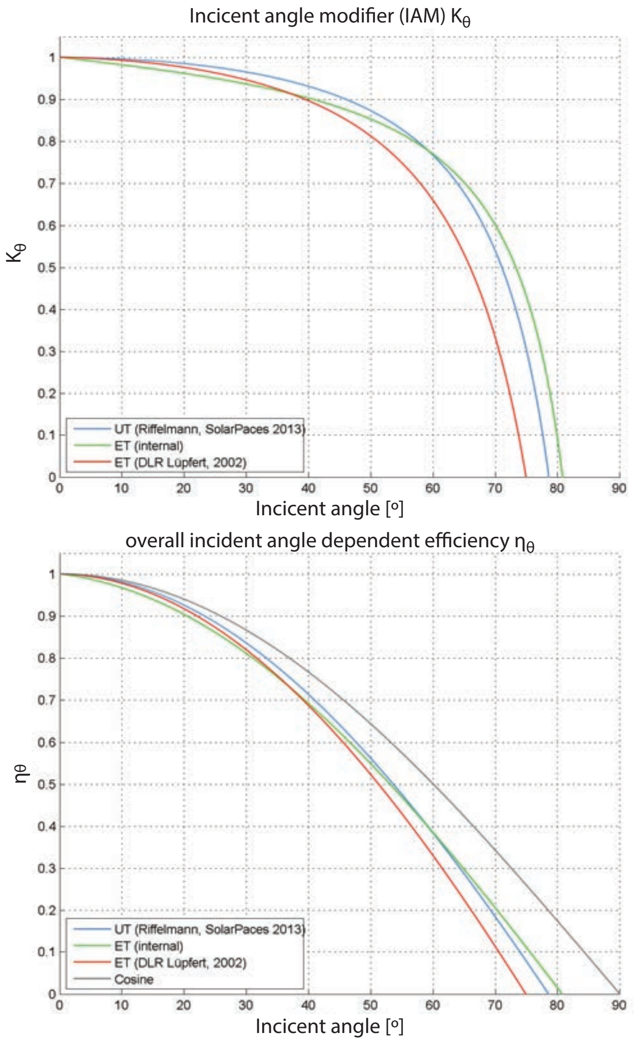


Figure 44: Parabolic trough incident angle modifier (upper) and collector efficiency (bottom) vs. angle of incidence

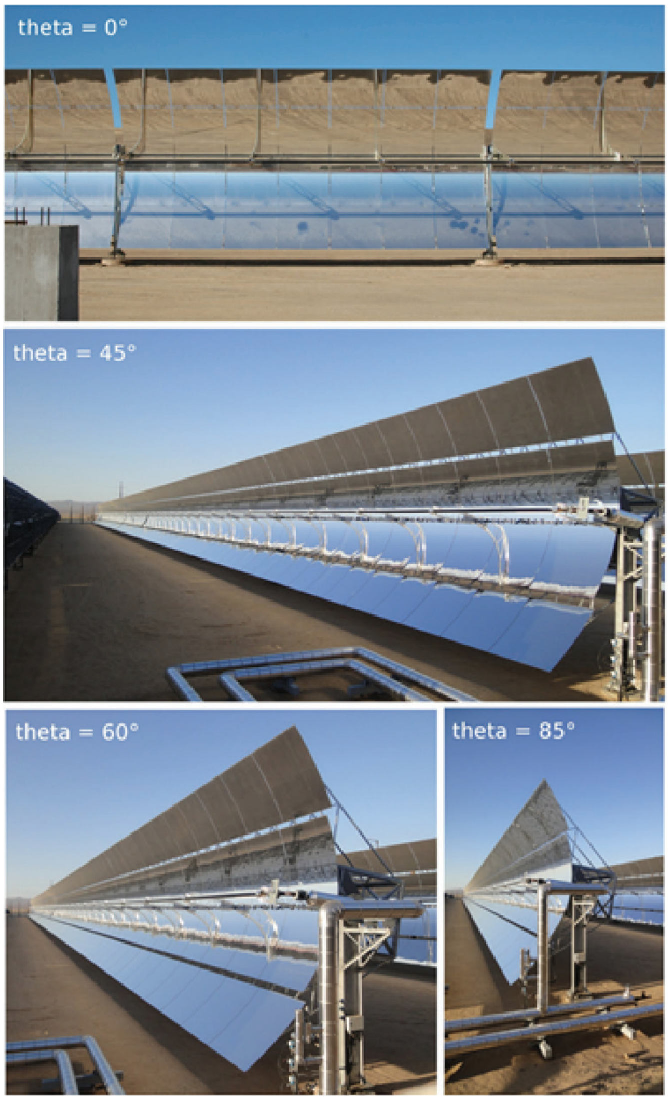


Figure 45: Angle of incidence affects effective reflector area

2.6.5 Thermal Losses

The thermal losses of a parabolic trough collector are largely independent from the collector type or structure and can be reduced to the HCE properties. Thermal losses result from thermal radiation, convection and heat conduction. The actual absorber tubes used in parabolic trough power plants are evacuated to reduce the thermal losses drastically.

The thermal losses of a receiver depend on the absorber surface size, the absorber tube insulation and the temperature difference between absorber surface and surrounding temperature. Hence, it is also depending on the operation temperature of the HTF. With increasing operation temperature, thermal losses are increasing as well. Tests were performed on a Solel UVAC3 absorber tube at ambient temperature of 23°C. These results are depicted in Fig. 46 as example.

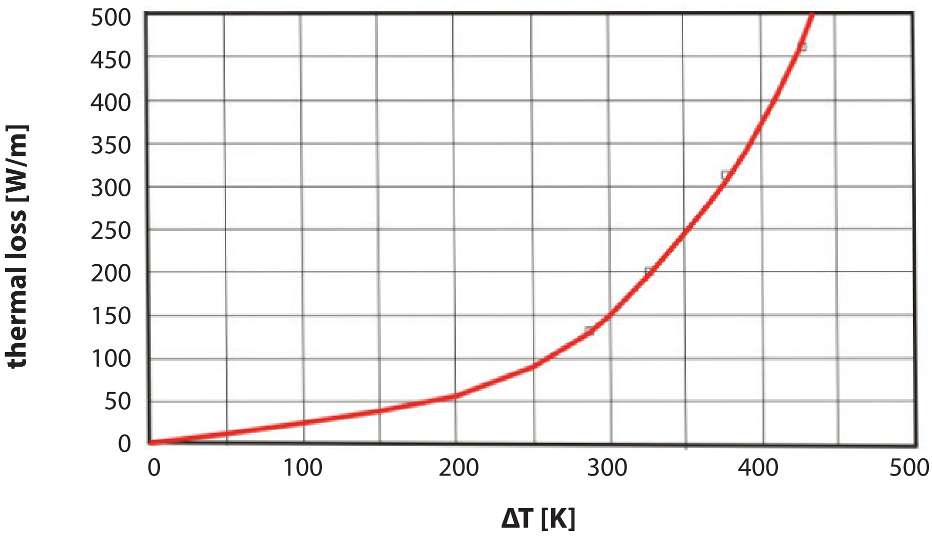


Figure 46: Thermal loss at the Solel UVAC 3 receiver: Measurement points and approximated function (DLR)

The actual PTR70 absorber from Schott solar shows considerably lower thermal losses; they are below 250 W/m (@400°C); smaller than 175 W/m (@350°C) and below 125 W/m (@300°C), respectively [28].

Thermal losses are low enough to keep temperature levels of the glass tube low enough for birds to rest on them during operation Fig. 47.

Figure 47: Thermal loss of current parabolic trough absorbers are low enough for birds to rest on the glass envelope (image © E. Lüpfert, CSP Services)

2.6.6 Operation Temperature

To date, high-boiling, synthetic thermal oil has been applied as heat transfer medium in parabolic trough solar fields. Due to the oil’s limited thermal stability, maximum working temperature is limited to scarcely 400 °C. This temperature requires to keep the oil pressurized (approximately 12 to 16 bar). This is why collector tubes as well as expansion reservoirs and heat exchangers must be of pressure resistant design. Relatively high investments are thus required.

Hence, as an alternative, molten salt has been proposed as heat transfer medium. Molten salt is characterized by the advantages of lower specific costs, a higher heat capacity and thus potentially higher working temperature (about 550 °C) and less heat exchangers at the storage tank, on the one hand, and by the higher viscosity of the medium and a higher melting temperature, requiring trace heating, on the other hand. Due to the higher heat capacity, pumping power requirements are still expected to be lower when compared to thermal oil. To date, only prototypes or demonstration plants of this variant have been built.

Recently, the direct steam generation was examined. The advantages are the higher possible working temperature of steam as a working medium and that there is no secondary heat transfer fluid loop required including the necessary heat exchangers. The expected problems related to evaporation of water in horizontal tubes (including two-phase flow and thus different heat transmission) can be solved by available technology (forced-circulation boiler with a relatively high recirculation rate and water/steam separator). It is thus possible to directly generate saturated steam by line focusing collectors. However, the high steam pressure (usually between 50 and 100 bar) requires a relatively high tube wall thickness.

Due to the growing demand of dispatchable energy, the advantages of molten salt seem to overbalance the advantages on direct steam generation.

As of today, all commercially operating parabolic trough solar plants are using synthetic oil as HTF with more or less the same operation temperature of 393 °C. The ENEL collector has been tested for molten salt application in a 5 MW demonstration plant. The Ultimate Trough is available for oil and for molten salt applications.

The German based company Solarlite built the first commercial parabolic trough power plant (5 MWe) for direct steam generation in Thailand. The operating parameters are 330 °C and 30 bars pressure [9].

	Heat transfer medium	Max. operating temperature (°C)
LS-2	synthetic oil	393
SGX-2	synthetic oil	390
LS-3	synthetic oil	393
EuroTrough	synthetic oil	393
Sener Trough 1	synthetic oil	393
SkyTrough	synthetic oil	391
HelioTrough	synthetic oil	393
SENERtrough-2	synthetic oil	393
LAT 73	synthetic oil	393
Ultimate Trough	synthetic oil	393
	molten salt	550
Airlight	air	650
Solarlite	water/steam	500

Table 3: Concentration ratios of selected parabolic trough collectors

2.6.7 Torsional Stiffness

A solar collector has to withstand frequent (operational) wind loads without losing optical efficiency and high (surviving) wind loads without a damage of the supporting structure. As a parabolic trough collector is an elongate structure that collects torsional loads over a large collector length of up to 240 meters (Ultimate Trough), the collector stiffness must be high. The horizontal and vertical forces are taken by the pylons at each SCE end, only the torsional moment has to be carried through the supporting structure to the collector's fix point – the drive pylon. Therefore, torsional stiffness is of central importance when designing a parabolic trough collector.

In addition to the other beam spreading mechanisms as specularity or sun shape, the collector torsion may have a huge impact on the total collector error.

Torsion is caused by wind loads, friction or unbalance action on the collector. Usually, the collectors are balanced, so that the deformation from unbalance can be neglected. Friction in the bearings is depending on the friction coefficient of the bearings, the weight force on the bearing and the diameter of the axle. Due to the low SCE length and the resulting low collector mass per pylon friction is not a factor for smaller collectors (LS-3 size). For larger collectors deformation from friction might be of considerable interest. On the other hand the breakaway moment of the sleeve bearings stabilizes the collector against deformations resulting from smaller operation wind loads. However, the torsional stiffness must be high enough to limit the collector torsion in such a way that the mean collector intercept is still acceptable.

It is not possible to define a general applicable maximum deformation limit, as the influence on the intercept value and therefore on the collector efficiency depends on many factors not least the concentration ratio. So the same twist of two similar troughs with a dissimilar concentration ratio as differentiator has a higher influence on the intercept factor for the trough with the higher concentration ratio. Hence, the optimum stiffness is a function on structure costs and collector efficiency. A stiffer structure usually results in higher structure cost on the one hand, but on the other hand it collects more energy what results in a smaller collector field.

The novel collectors are longer than the collectors of the first generation. Thus, a higher torsional stiffness is required in order to achieve an equivalent or even better optical efficiency. As example the stiffness of the EuroTrough is significantly lower than the stiffness of the about 90 meter longer Ultimate Trough or the about 40 meters shorter HelioTrough collector. This can be seen in Fig. 48, where the calculated collector rotation is depicted. At the end of both trough collectors a torque of 1 kNm is applied. The resulting rotation at the end of the EuroTrough collector wing (x = 75m) is higher than the corresponding rotation of the Utlimate Trough or the HelioTrough collector.

The graph of the HelioTrough is continuous unlike the graphs of Ultimate Trough or EuroTrough. At almost every available collector the high stiffness of the torque box or tube is interrupted between the SCEs. The SCEs are connected by so-called torque transfer tubes. These tubes have a lower stiffness than the main supporting structure, thus, gaps in the rotation graphs appear. Still, due to its short length, the impact on the overall SCA stiffness is low. The HelioTrough has a constant stiffness as no torque transfer tubes are used.

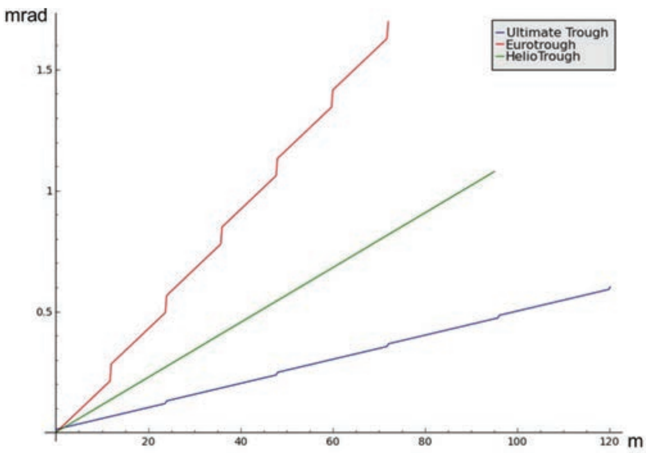


Figure 48: Collector rotation of Ultimate Trough (blue), EuroTrough (red) and HelioTrough (green)

The lower torsional stiffness of the EuroTrough does not necessarily lead to a higher distorsion. Due to the smaller aperture area the acting loads are smaller to. As example the torsional torque due to friction in the bearings is plotted for the EuroTrough and the Ultimate Trough in Fig. 49. This twist depends on the weight of the collector, the torque transfer tube diameter, the bearing arrangement and the friction coefficient of the bearings. The resulting collector torsion is plotted in Fig. 49. Even though the stiffness of the Ultimate trough is about four times higher, the distorsion under friction loads is similar (1.7 mrad at x = 75m to 2.3 mrad for the EuroTrough).

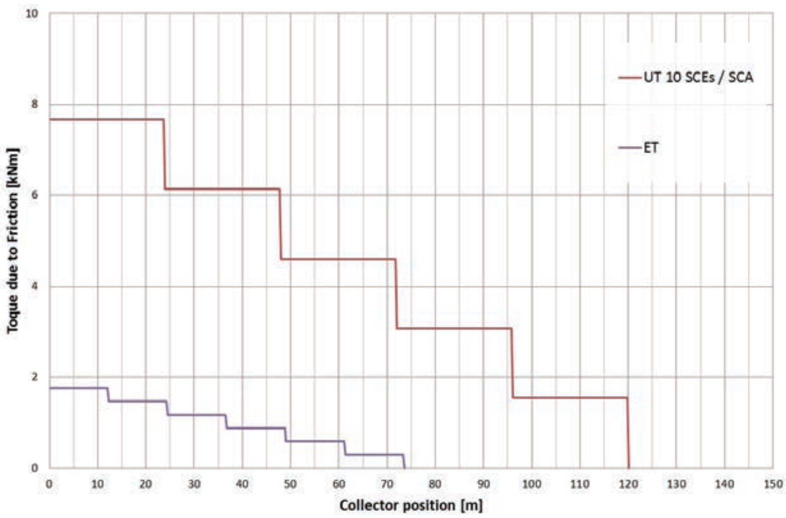


Figure 49: Torque due to friction for UT (red) and ET (blue) [29]

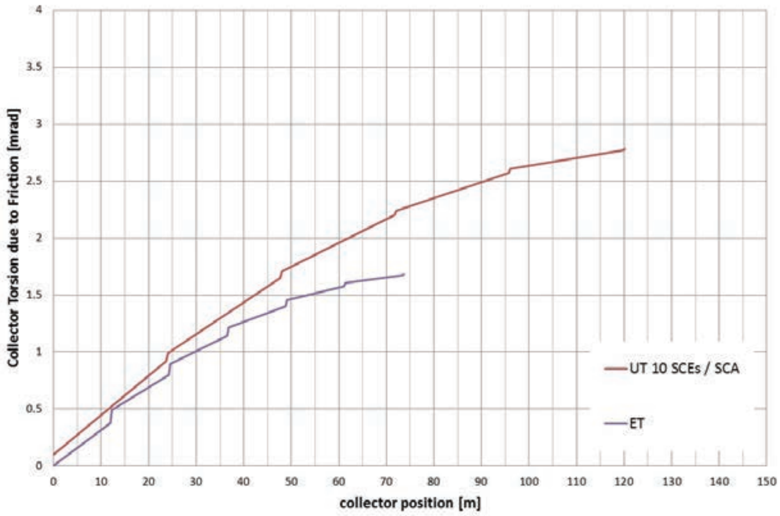


Figure 50: Collector torsion of UltimateTrough (red) and EuroTrough (blue) [29]

2.6.8 Collector tracking end positions in operation

To allow an undisturbed operation, an angular range of 0° to 180° is necessary; in the region around 0 and 180 degrees direct irradiation(DNI) is rather low and shading by other collectors is rather high. Thus, the energy that is collected in the early morning as well as in the evening is much less than at solar noon, where a much higher DNI and no shading appears.

In order to reduce the wind loads acting on the collector and thus the required strength of the supporting structure to a minimum, the collector moves to the position that results in the lowest wind pressure coefficients - the so called stow position. Usually that position is slightly lower than the horizontal position, e.g. around -20° to -5°.

At a gathering storm, the collector has to move to its stow position. Since for this a certain time is required (depending on the respective position), the collector must start driving already 20 minutes before the occurrence of an expected high wind speed. To reduce this time the UT has two stow positions.

Most collectors also have a maintenance or washing position (about -20°). In this position the HCEs are closer to the ground and thus easier to install or wash.

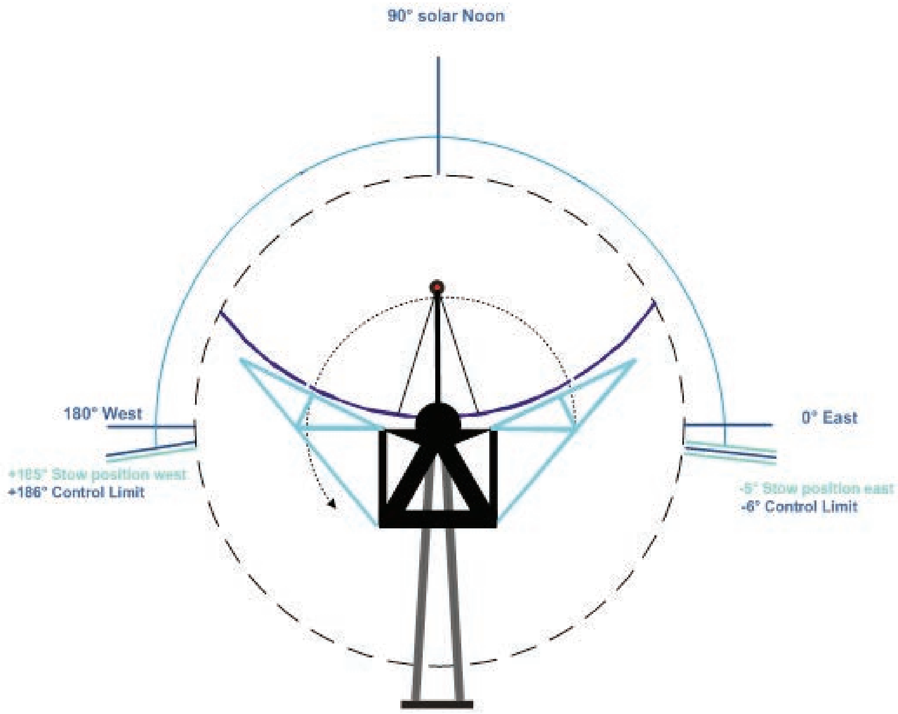


Figure 51: Angular Range UltimateTrough

2.6.9 Drive system

In the middle of a collector, a so-called drive pylon is installed. This drive pylon acts as collector fix point and drive unit that tracks the collector. Because the middle pylons can take only a small amount of torsional and longitudinal force, the drive pylon must take all loads in these directions.

In the parabolic trough technology, the cost efficient hydraulics have prevailed. At that technology two hydraulic pistons are connected to a kind of axle. A linear displacement is translated into a rotation by levers. The effective lever is depending on the collector's respective elevation angle. As the maximum hydraulic pressure is constant the highest moment can be taken or applied when the effective lever is large. To use the two hydraulic cylinders effectively and to resist maximum possible torsional wind loads, the lever arms are usually arranged so that they are greatest in the stow position.

The maximum torque of the drive system can be adjusted to the designated site conditions by the selection of maximum pressure in the hydraulic pistons or piston dimensions. Hence it has not to be paid for drive power that is not required.

Usually hydraulics require very little maintenance. The seals have to be checked in a yearly interval and the hydraulic oil has to be checked for water content. If of the water content surpassing a certain level, the oil has to be replaced.

Another drive variant is the hydraulic rotary drive as used by the SGX-2 collector. Two tooth bars are moved counter-rotating by a hydraulic piston. This linear translation is then converted to a rotation by a toothed axle stiffly connected to the collector.

Figure 52: SGX-2 (Nevada Solar One) drive

Figure 53: SGX-2 (Nevada Solar One) drive details [30],[31]

The SkyTrough drive system uses a helical sliding spline hydraulic rotary actuator. Customized specifically for the concentrated solar power market, this drive generates 48 kNm of output torque yet is capable of rotating the collector assembly in precise 0.1° increments through the entire 240° of total rotation. The helical rotary actuators use a low hydraulic displacement to drive through their rotation cycle, which facilitates the use of a small pump and motor to supply the high-pressure fluid to the actuator. Coupled with a small electric motor, with support for 110 Vac and 220 Vac single and three-phase power input, is a single gear pump that provides the hydraulic pressure needed to drive the actuator in the both the low-speed tracking as well as high-speed stow modes.

The tracking of a parabolic trough is usually controlled by a programmed sun algorithm and a local sensor, the so-called sun sensor. The sun sensor is built up from two equally sized photovoltaic cells that are placed behind the heat collecting element facing the sun. The shadow of the HCE shades both cells to the same quantity when the collector is ideal elevation. When the voltage measured from both cells is dissimilar, the controller can calculate the theoretical deviation from the ideal collector elevation and starts readjusting.

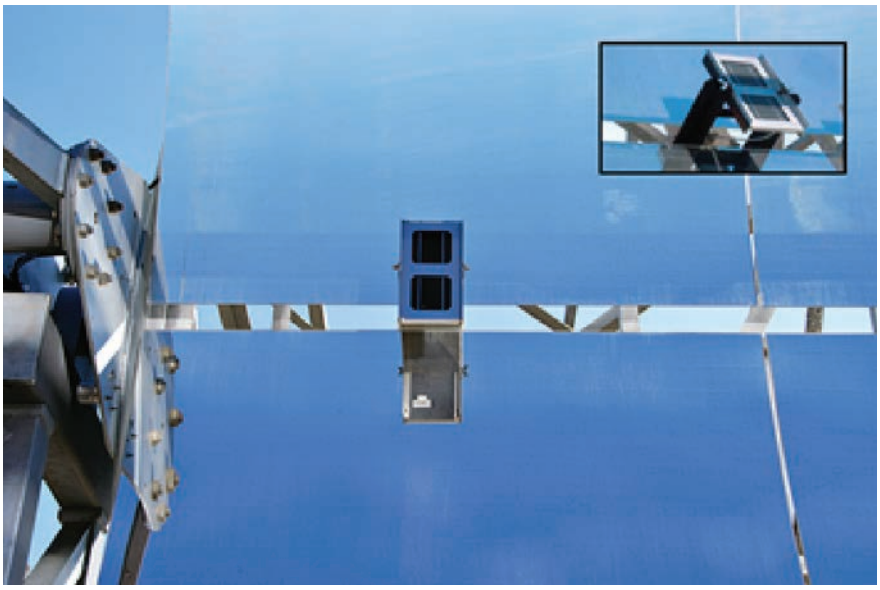


Figure 54: Sun sensor of the EuroTrough [32]

	Type	Angular Range	Typical Holding Moment in Stow Position	Tracking Accuracy
EuroTrough	Two hydraulic pistons + axle	196°	100 kNm	< 1.0 mrad
SkyTrough	Hydraulically self-locking, helical geared actuator	240°	Max. 200 kNm	1.0 mrad
UltimateTrough	Two hydraulic pistons + axle	192°	About 320 kNm	< 1.0 mrad

Table 4: Drive types of selected parabolic trough collectors

2.6.10 Speed of Process

The different collector systems pursue different assembly concepts. Depending on the country (staff costs / training degrees), a particular concept fits better than another.

Space Frame Structures (SGX-2 / Sky Trough):

Space frame types are assembled without jigs and completely by hand, usually. This requires a high precision of the prefabricated components, since no tolerance compensation can take place. The assembly errors are therefore entered in the mirror surface. The assembly process takes place directly in the field, thus, no assembly hall is necessary.

EuroTrough / SENERtrough:

The EuroTrough and the SENERtrough (and many others) are mounted in a temporary assembly hall. Jigs are used to connect the elements in such a way that tolerances are compensated. The elements that hold the mirrors at the EuroTrough collector for example, are mounted in a device so that the parabola of the mirror is exactly achieved. All steel components beneath it can therefore be manufactured with a conventional steel construction tolerance. Tolerance compensation takes place via larger holes. Experienced data shows that 0.5 - 1 collectors can be built per assembly line and hour. However, this strongly depends on the local infrastructure and on the experience of the workers.

A good reference value to compare the assembly speed of parabolic troughs is "mirror area per assembly line and hour". This allows for a comparison to the larger parabolic troughs of the next generation.

UltimateTrough / HelioTrough:

UltimateTrough and HelioTrough are manufactured in principle as the SENERtrough or the EuroTrough collector, but there is an additional jig, in which the negative of the nominal parabola geometry of the reflector panels is formed. In this, the mirrors are inserted and connected to the steel structure using a tolerance compensating connection. Thus, a very good fit to the desired shape is achieved, which leads to significantly improved collector efficiency.

Within the assembly halls it must be further distinguished between manual, semi-automatic and fully automatic production. Thus, at sites with high personnel costs it might be reasonable to reduce staff and replace it by automatic production lines as used in the automotive industry. Generally, a semi-automatic production is preferred, where for example the reflector panels are moved by an automatic suction device but the connections are screwed by hand.

One advantage of the assembly hall is the simplified and more accurate quality control. By means of a built-in measurement device each built collector element can be measured easily. Only these collectors, which meet the required optical standards are delivered to the collector field then. For non-sufficient collectors errors can be quickly identified and repaired.

2.6.11 Maximum wind velocity during operation and in stow position

During daytime, when direct normal radiation is available, the collectors are tracking the sun. In the evening, around sunset, the collectors are sent to 'stow position', where they will remain until tracking starts again on the next morning. The wind protection position is characterized by the lowest torsional loads within the collector's tracking range; at the same time, wind protection position must be at an elevation angle where the optical axis points below or equal to the horizon to prevent any potential damage to HCEs due to concentrated solar radiation under low flow conditions during plant startup and shut down. Wind protection position must be both a position providing protection from excessive wind loads and from the sun.

If during normal operation, i.e. while the collectors are tracking the sun, wind velocity increases and exceeds a certain limit, a wind alarm is released and the collectors are returned to wind protection position. The drive system must be designed to rotate the collectors fast enough to make sure that the collectors have reached wind protection position before wind speed has risen to above 20m/s [33]

Therefore two wind scenarios with the respective wind speeds have to be considered:

- Survival wind speed
  Position: stow
  Design criterion: Structural stability

- GoToStow or transient wind speed
  Position: any
  Design criterion: Structural stability + maximum drive power

Usually, the collectors are adapted to the site boundary conditions, therefore it is not useful to compare the collectors based on their allowable wind speeds. Top of that the data given by the manufacturers are based on different codes and are therefore not directly comparable. To give an indication the survival wind speed as 50-year wind speed without any safety factors and the maximum operation wind speed as 3-sec-gust value is given for a built EuroTrough in table 5.

	Survival wind speed [m] (5o-year wind speed; 3-sec-gust)	Max Operational wind speed [m/s] (3-sec-gust)
EuroTrough	37.6	15

Table 5: Survival and maximum operational wind speed of selected parabolic trough collectors

2.6.12 Collector mass (w/o HTF)

The weight of the collector is often used as indicator for the overall costs of the solar field. But without further knowledge on the optical performance the specific weight and the specific costs of a collector has little significance.

The size of a solar field is strongly affected by the optical performance of the collector. A power plant with a "cheaper", lighter collector with moderate optical performance will need a larger solar field than one with a heavier collector with better optical precision. But it has to be determined if a cheaper collector is able to outweigh its shortcomings by its costs or if the heavier collector is worth the additional expenses.

A holistic approach is needed to evaluate the performance of a collector. This is done by running thorough power plant simulations over the complete operation period to evaluate its financial performance.

The optimum ratio of the specific costs and optical performance characterizes a good collector.

Nevertheless, the masses of selected collectors are listed below.

	Collector Mass [kg/m^2]
SGX-2	22
EuroTrough	40
UltimateTrough	42

Table 6: Collector mass of selected parabolic trough collectors

It is noticeable that the specific mass of the new UltimateTrough collector is higher than the one of the EuroTrough. This is due to the larger structure of the UltimateTrough, which is exposed to higher wind loads. In return, the overall number of expensive parts like ball-joint assemblies or header pipings is reduced by the structural scale-up. So the overall performance of the UltimateTrough is better because of the cost savings on the parts and the higher optical performance (see 3.4 and 4.3).

2.6.13 Material of reflector and collector support structure

The main requirements for appropriate mirror materials are their reflective properties. The reflectivity must be high. The reflectivity of a surface is a number that indicates the fraction of the incident radiation that is reflected by the surface. Reflection can be distinguished in specular reflection and diffuse reflection. Specular reflection means that the light that comes from a single incoming direction is reflected into a single outgoing direction. Specular reflection is mirror-like reflection. According to the law of reflection the direction of the incoming light and the direction of the outgoing light have the same angle with respect to the mirror surface normal. At diffuse reflection, on the contrary, the incoming light is reflected in a broad range of directions. In CSP applications, only specular reflectivity is of interest, because the reflected radiation must have a defined direction. The decisive quality criterion for efficient mirrors is, hence, the "solar weighted specular reflectivity" [2].

The most common parabolic mirrors today consist of silver coated glass mirrors as used in the SEGS plants for more than 25 years. A special low-iron glass is used to increase the light transmission in the solar spectrum. High geometric mirror accuracies can be reached by the available glass forming procedures. Due to available production and forming procedures the maximum available facet size is limited to about 2 x 2 meters. Therefore the mirror surface of a collector element is set together from smaller facet elements.

The solar mirrors are structured in multiple layers. As reflective surface the glass is coated with a thin silver layer. To protect the silver layer different layers of copper and lacquer are applied as top coats.

The average solar weighted direct reflectivity of the Flabeg reflector panels is indicated to be 94.4% [http://www.flabeg.com/uploads/media/FLABEG_Solar_Parabolic_07.pdf].

Besides Flabeg also other glass reflector panel suppliers such as Guardian or Rioglass have similar products on the market.

The reflector panels account for a considerable part of the solar field investment for a parabolic trough power plant. There are ongoing efforts to find alternative materials that could lower the solar field costs.

In the last years a number of collector systems using reflector panels with a silver coated polymer film as reflective surface were developed. This polymer film can be applied to a backing material e.g. aluminum sheets that have advantageous properties compared to glass. This might reduce the breakage and therewith the operation and maintenance efforts.

The company Skyfuel, which commercializes the ReflecTech technology, indicates the reflectivity to be 94%. Comparable products of other suppliers as 3M are on the marked, today.

Another approach is used by the German supplier ToughTrough. Here thin-glass mirrors are used as stiff sandwich facet. As back layer a thin steel sheet is used. The space between glass and steel is filled with a polymer foam.

	Reflector Type	Structure material
LS-2	monolithic solar glass	steel
SGX-2	monolithic solar glass	aluminum
LS-3	monolithic solar glass	steel
EuroTrough	monolithic solar glass	steel
Sener1	monolithic solar glass	steel
HelioTrough	monolithic solar glass	steel
SenerTrough 2	monolithic solar glass	steel
SkyTrough	reflective polymer film on aluminum sheet	aluminum
LAT 73	reflective polymer film on aluminum sheet	aluminum
UltimateTrough	monolithic solar glass	steel

Table 7: Reflector and structure material of selected parabolic trough collectors

2.6.14 Cleaning systems for reflectors and absorber tubes

Considering the energy production of a parabolic trough plant, key factors like high mirror reflectivity or less transmission losses through the absorber tube have to be guaranteed. These factors depend for example on a clear mirror or tube, thus making an accurate and continuous cleaning of the mirrors essential. Through these arrangements, energy production of the plant can be ensured and maximum efficiency is reached.

The facility operators use different ways to ensure cleanness of their parabolic trough collectors.

First there is the conventional method of cleaning the collectors with simple brushing and a jet of water (Fig. 55). This needs a high amount of water and also employees. On the other hand places which need extra or further cleanness can be edited without much efforts.

Figure 55: Mirror washing

To avoid personal extensive cleaning processes and to reduce although the water usage several automatic cleaning systems were manufactured. Respectively adapted to the parabolic trough plant the cleaning system has to be hard-coded and designed. While a high cleaning degree is required the system must ensure cleaning without any damage.

An example for such an automated cleaning system is the so called PARIS produced by the company SENER (Fig. 56).

PARIS is a full automatic unmanned vehicle produced and designed for cleaning the plant by night. It cleans the mirrors vertically, from the top to the bottom. The two semi parabolas are cleaned simultaneously with wet brushing, while the tube is cleaned using a water jet

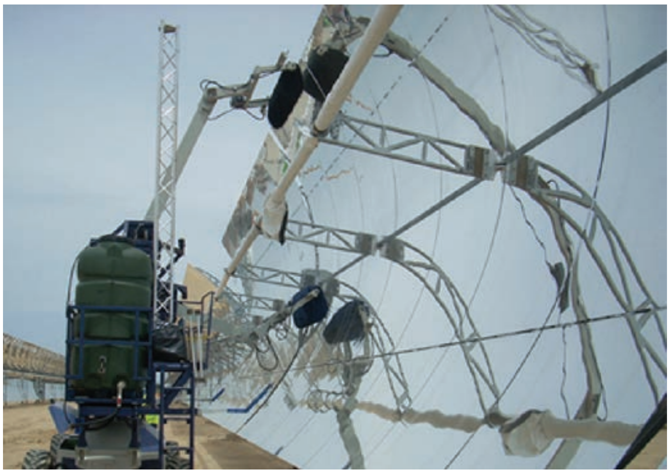


Figure 56: Autonomous cleaning vehicle PARIS

PARIS starts the cleaning process at the entrance of a loop and calibrates and corrects its position using its GNC software. Automatically it completes a whole loop and aligns itself to start with the next loop. The fact that the cleaning system is programmed to work in intermittent mode is a great advantage. That means the cleaning system stands in a fixed position while cleaning. This static method of operation reduces mirror damages and cleaning faults.

Figure 57: Cleaning vehicle at Shams power plant (Abu Dhabi)

There are also other semi-automated cleaning vehicles. For example the cleaning vehicles used in Shams 1 (Abu Dhabi). They require a driver and clean the mirrors while moving in parallel to the collectors. In this case human intervention and motor fuel in addition to the electrical components is needed.

2.6.15 Specific energy and water consumption for cleaning

To calculate the exact energy need for a washing cycle is very complex because factors like water allocation and preparation, fuel need and electrical consumption have to be considered. It also depends drastically on the location and on the predominant dust deposit.

Of course with rising water usage or required motor fuel the energy consumption increases, too.

It is for sure an advantage to use only as much of water as needed for a washing cycle. Wet brushes are cannier than a full jet of water.

Specific data for the water consumption of such systems are typically not available to the public. An exception is the parabolic trough called Airlight produced by Airlight Energy [8]. Airlight mention a water usage of nearly 1000 l per week for cleaning and maintenance for an aperture size of 2679 m^2.

2.6.16 Types of flexible joints between collectors

The HCE of the collectors are moving due to the tracking of the sun (rotation) and because of thermal expansion (translation). These movements are relative to the fixed field piping and to independently moving collectors.

To allow for a relative movement of the HCEs flexible tube elements are necessary. Three concepts (also in combination) have been used so far.

2.6.16.1 Flexhose interconnection

Characterized be a thin-walled internal metal tube and an external metal meshwork. The meshwork supports the internal tube against the internal pressure of the heat transfer fluid.

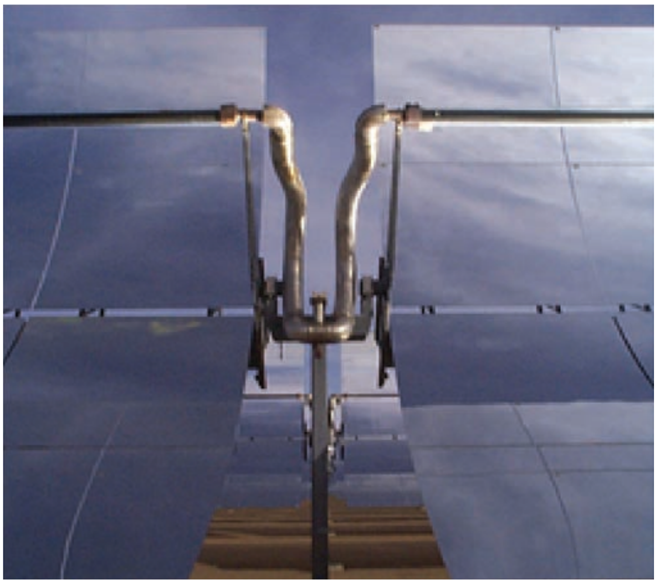


Figure 58: Flexhose interconnection

2.6.16.2 Ball-Joint interconnection

Characterized by build-in ball-joints with rotational and tilt degrees of freedom. Manufacturers are e.g. ATS and Hyspan.

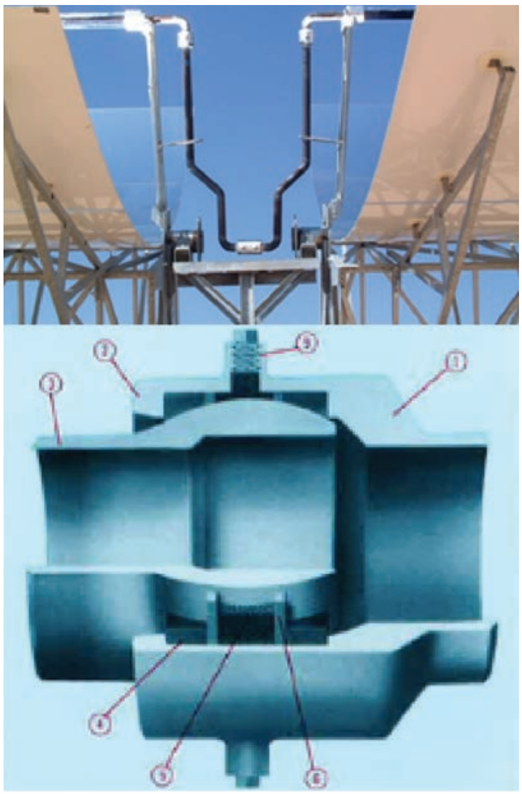


Figure 59: Ball-Joint interconnection (left: installed, right: Cut-away of a ball-joint element)

2.6.16.3 Swivel joint with compensator interconnection

This interconnection is characterized by a separation of the rotational and translational movement. To compensate for the translational movement a pressure-resistant corrugated metal hose ("compensator") is used. The rotational movement is enabled by multiport swivel manufactured e.g. by Senior Flexonics (Fig. 60).

Figure 60: Multiport swivel

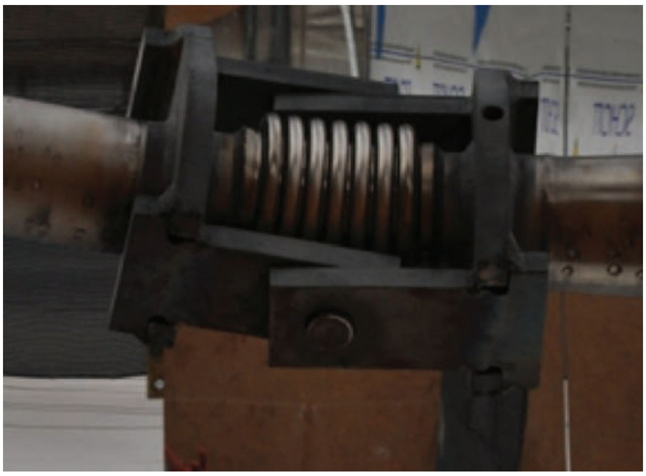


Figure 61: Supported compensator

3 FINANCIAL PARAMETERS

This chapter will show how the financial performance of a of parabolic trough power plant is estimated. The results are presented for plants of different sizes and with or without storage.

3.1 OVERALL PERFORMANCE CALCULATION OF A PARABOLIC TROUGH POWER PLANT

Because solar plants rely on an intermittent fuel supply - the sun - it is necessary to model the plant's performance on an hourly (or finer resolution) basis to understand what the annual performance will be based on plant design and a user-supplied operating strategy.

Using precise performance data of the parabolic trough collector and long-time average weather data as well as considering capital costs, operation and maintenance (O&M) cost allow to estimate the power plant's financial performance during its operation period.

3.2 LEVELIZED COSTS OF ELECTRICITY

Levelized cost of electricity (LCOE) are often used to compare different options for power generation. They are calculated based on a simplified method. For LCOE calculation, annual power generation and cost data are required.

To calculate the power generation cost using the annuity method, the amortization time n is usually set at 20 to 25 years, i.e. the expected technical lifetime of the system, and a certain interest rate *p*.

In order to calculate the LCOE for several years, the formula given below is applied:

$$LCOE = \frac{\sum NPV(\,Investion(€) * a) + \sum NPV(\,Expenses\ (€))}{\sum(\,Annual\ energy\ production\ (kWh))}$$

Here the summation symbol Σ refers to the sum over the annuity/depreciation period, and NPV (net present value) means today´s value of the future annuity/expenses discounted by the inflation rate. In other words: LCOE takes into account the present value of all the future expenses (O&M,...) and the present value of all the future loan payments, summing them, and dividing the total by the total amount of energy that will be produced.

3.3 SOFTWARE

The performance calculations were made using the NREL's simulation tool SAM [35]. SAM is a performance and financial model designed to facilitate decision making for people involved in the renewable energy industry. The software makes performance predictions and cost of energy estimates based on installation and operating costs and system design parameters. Main input variables are: Installation costs including equipment purchases, labor, engineering and other project costs, land costs, and operation and maintenance costs

- Collector and receiver type, solar multiple, storage capacity, power block capacity for parabolic trough systems
- Analysis period, real discount rate, inflation rate, tax rates, internal rate of return target or power purchase price for utility financing models
- Building load and time-of-use retail rates for commercial and residential financing models
- Tax and cash incentive amounts and rates

3.4 REMARKS ON OVERALL PERFORMANCE CALCULATIONS OF PARABOLIC TROUGH COLLECTORS

It is intriguing to think of a market-wide comparison of all currently available parabolic trough collectors and to nominate a winner. But this is hardly possible due to a number of reasons:

» The manufacturers do not provide important collector data required for performance evaluation such as:

- specific costs (€/m^2)
- incident angle modifiers (cf. 0)
- precision during assembly
- tracking error

This data would have to be estimated using experienced data.

» The target variable of the comparison usually is the *levelized* cost of electricity (LCOE). The LCOE for a specific CSP technology (e.g. parabolic trough) of the current generation is about the same order of magnitude. Thus, very precise performance data is necessary to allow for a reasonable and fair comparison. If the performance data is not provided by an independent test center using a standardized measurement procedure, it is likely that the performance data is beautified to some degree. The results would be neither reliable nor directly comparable.

» Different scenarios that show significant variation in the LCOE and would allow for reasonable performance comparisons:

- different CSP technologies (parabolic trough, power tower, linear Fresnel, dish)
- technology leaps (e.g. molten salt as HTF) or scale up
- locations with varying solar irradiance

Given the reasons stated above, this study will compare different parabolic power plants using the current collector EuroTrough (ET). It is well established and evaluated, so reliable performance data and manufacturing costs are available. The comparison will show the impact of the plant size and a thermal storage. A comparison of the EuroTrough to the next generation of parabolic troughs will show further opportunities to decrease the LCOE.

3.5 COMPARISON OF PARABOLIC TROUGH POWER PLANTS: ELECTRIC OUTPUT AND THERMAL STORAGE

Power plants of different sizes and with or without thermal energy storage system (TES) were evaluated. All configurations use the EuroTrough collector, as it is well established and evaluated. Table 8 shows the results.

		50 MW	50 MW	100 MW	100 MW	200 MW	200 MW
		6h Storage	w/o Storage	6h Storage	w/o Storage	6h Storage	w/o Storage
Investment costs	M€	**213**	**125**	**392**	**232**	**726**	**420**
Earth works & Foundations	M€	7	4	14	9	28	16
Parabolic trough costs	M€	58	35	111	67	215	120
HTF system (with HTF)	M€	14	7	26	14	50	27
other solar field costs	M€	5	3	8	5	15	9
power block	M€	60	57	110	105	200	190
storage	M€	40	0	69	0	120	0
EPC costs	M€	22	13	41	25	75	44
Owner costs	M€	7	4	12	8	22	13
spec. Investments	M€/MW	4	3	4	2	4	2
annuity of investment costs	M€	14	8	25	15	47	27
O&M costs and insurance	M€	6	4	12	7	22	13
spec. O&M costs	k€/MW/a	128	75	118	70	109	63
Total annual costs	M€/a	20	12	37	22	68	40
LCOE	**€/kWh**	**0,108 €**	**0,111 €**	**0,098 €**	**0,102 €**	**0,094 €**	**40**

Table 8: Parabolic trough power plant configurations

REMARKS:

- Parabolic troughs: With mirrors, absorber tubes and assembly
- Owner costs: E.g. permitting, surveys, consulting, financing,…
- Amortization time: 25 years
- Nominal interest Rate (or nominal discount rate): 8%
- Annual inflation rate: 2.5%
- DNI: 2500 W/m^2
- Solar multiple is optimized to fit each power plant

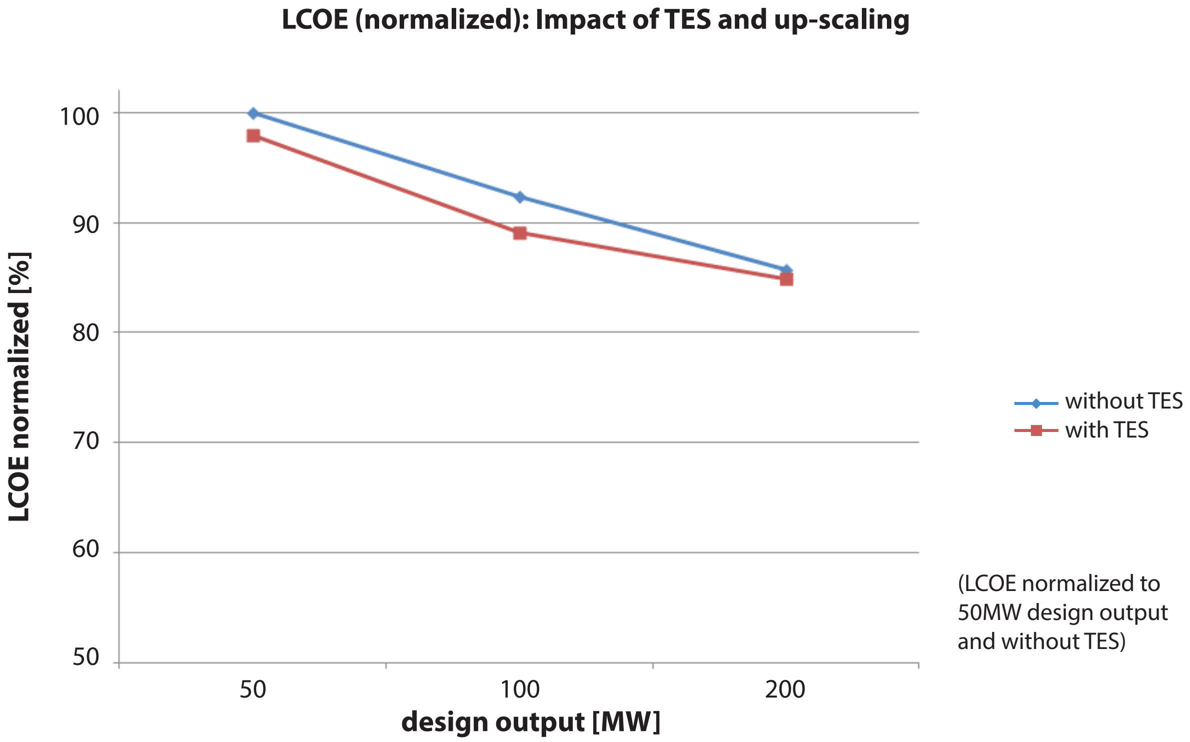


Figure 62: Normalized LCOE vs. name plate capacity ('design output')

In this case, the relative LCOE are more important as the absolute ones. Fig. 62 shows the relative LCOE, normalized to 50 MW design output and without TES. Two important effects are noticeable:

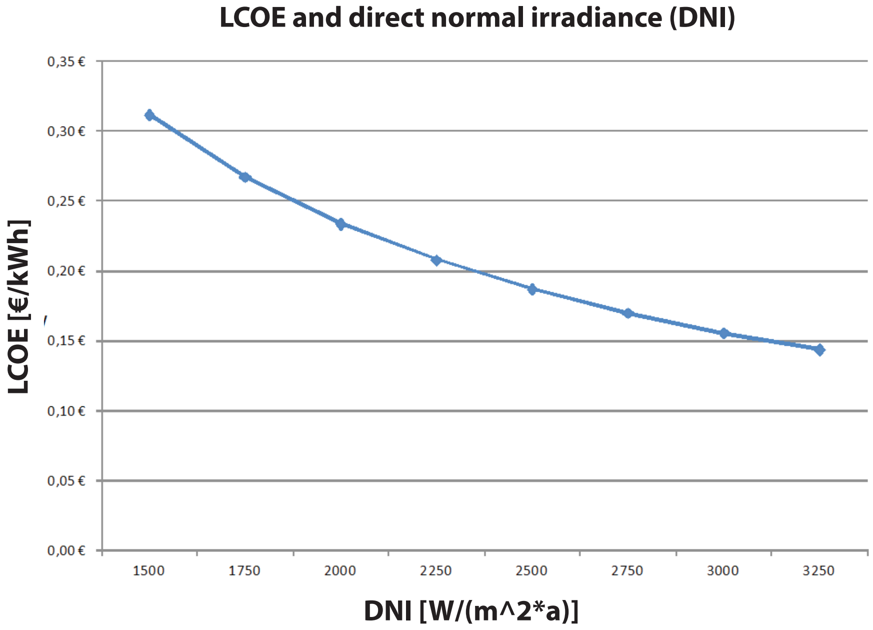
- LCOE decreases significantly due to the up-scaling of the design output (cf. chapter 4.4)
- At least for plants smaller than 200 MW LCOE decreases when a thermal energy storage system (TES) is incorporated into the power plant. This is because of the increased controllability of the plant and thus the better utilization of the turbine.

3.6 THE IMPACT OF SOLAR IRRADIANCE LEVEL ON LCOE

Of course the solar irradiance strongly affects the overall performance of a solar power plant. The direct normal irradiance (DNI) in Brazil varies strongly, from 1200 - 2400 kWh/(m^2*a) (cf. Fig. 63). Parabolic trough power plants are usually profitable in areas with a DNI of about 2000 kWh/(m^2*a) or higher.

Figure 63: Direct normal irradiance map of Brazil [36]

A parametric calculation was made to show the impact of the DNI on the LCOE. The results are shown in Fig. 64. The calculations were made for a 50 MW power plant with 6 h storage. As already stated above, the general trend is more important than the absolute numbers.



design output: 50 MW
storage: 6h
O&M and insurance: 3% of total investiment
Operation time: 25 years
Interest Rate: 8%

Figure 64: Impact of solar irradiance on LCOE

3.7 FINANCIAL PARAMETERS OF NEXT GENERATION PARABOLIC TROUGH COLLECTORS

There is only little information available on the performance of the next generation of parabolic trough collectors since only test loops were built to date (Flabeg/sbp's UltimateTrough and 3M/ Gossamer's LAT).

First performance measures of the UltimateTrough test loop are promising [18]. Riffelmann et al [18] compare solar fields using UltimateTrough and EuroTrough, both having the same annual output. The authors mention "significant reduction of parts [...] within the Ultimate Trough solar field, with related cost savings". Not only is the number of parts (e.g. drives, sensors, controls, swivel joint assemblies) reduced, also the number of pylons, pylon foundations and cross over pipes (cf. 2.4.2). Due to the smaller solar field the amount of heat transfer fluid (HTF) is reduced by 25% and also the HTF piping infrastructure. The paper states that the UltimateTrough solar field costs are about 23% less compared to the EuroTrough. With this cost reduction the levelized cost of electricity (LCOE) is decreased by about 11%.

4 TECHNOLOGICAL DEVELOPMENTS

4.1 GENERAL TRENDS

In Fig. 65 the development of specific parabolic trough power plant cost is depicted: In the course of the deployment of the SEGS plants by LUZ, significant cost reduction was achieved. Nevada Solar One was another step in this direction. In principle, the Spanish plants should have followed the experience curve (brown curve in Fig. 65) as pre-defined by the earlier US-American plants. Unfortunately, the numbers as observed by Hayward [37] do not exactly show the expected trend. Instead, specific costs of the Spanish plants are higher than expected.

The reasons for this may on the one hand be the fact that Spanish plants often include thermal storage, which obviously increases specific investment costs, but not necessarily levelized electricity generation costs (LCoE). Therefore specific investment costs cannot be considered an absolutely appropriate figure of merit here, but it is arguably the best one for which data is often available.

A second reason for costs not being reduced as expected from typical experience curves is the design of the Spanish feed-in tariff: It incorporated no degression, therefore any realized cost savings will remain unnoticed by the outside, as the projects will always cost as much as the tariff allows. The trend of the cost reduction observed is therefore not a characteristic of parabolic trough technology, but the result of a poorly designed feed-in tariff system.

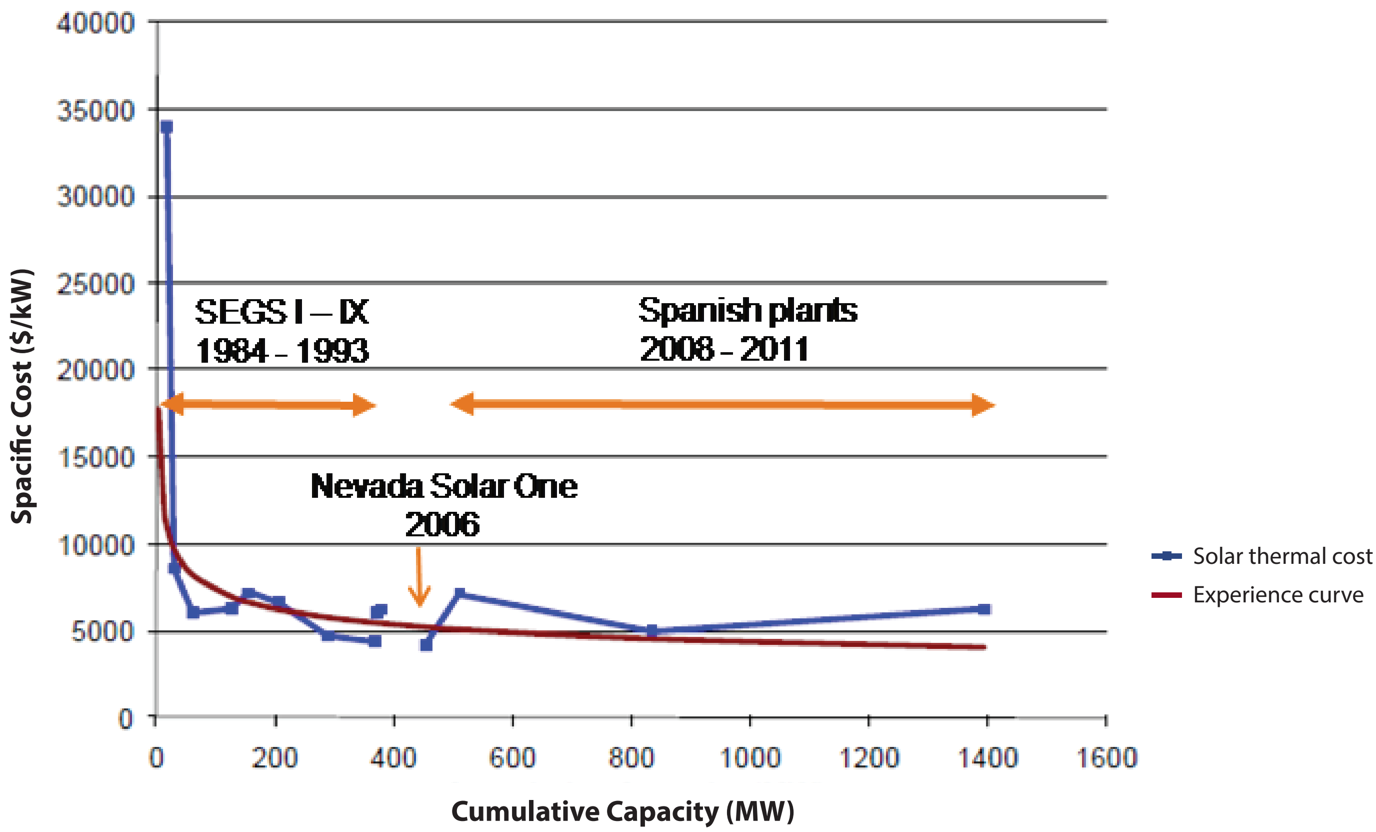


Figure 65: Specific cost of parabolic trough power plants vs. installed capacity (based on [37] with own additions)

[1] Specific cost in terms of 'monetary units per installed capacity' must always be read very carefully, as the numbers are often misleading: Costs and effects on energy output of larger solar fields and/or integrated storage is not reflected in such a number. Moreover, the real figure of merit is 'cost per energy', to be more exact: 'cost per energy that is produced when needed'. Still, as the general idea is conveyed by this chart, it has been used here for the introduction.

Two more recent parabolic trough plants shall be mentioned to show the variety of specific installed costs that can be found today: The 100 MW Shams 1 power plant in Abu Dhabi cost about $6000/kW [38], whereas the 50 MW plant in Godavari, India, cost about $3200/kW (estimate based on publicly available information and own calculations).

After LUZ had to file for bankruptcy in 1991 [39], [40], no proven collector design was available any more. Only in the late 90ies started the development of a new collector called 'EuroTrough'. This design used the geometry of the exisiting RP-3 mirrors from Flabeg which had already been used for LUZ LS-3 collectors [4]. The EuroTrough was then used for the Andasol and other parabolic trough power plants in Spain [41]–[43]. All other collectors in the Spanish plants are quite similar to the EuroTrough.

Subsequent developments like the HelioTrough [44], the UltimateTrough [45] and also the collector designs by Gossamer Space Frames / 3M [23] and Skyfuel [19] target at LCoE reduction through improving efficiency and reducing costs.

The advent of cost efficient high performance collectors like the UltimateTrough enables significant cost reductions. Cost reductions already possible today and an outlook what will very likely be possible in the next few years is shown in Fig. 66[46]. In this study, under given ambient (Daggett, CA) and financial conditions (simplified IEA method, 25 years, 8% IRR, 1% insurance rate) LCoE for a 'Spanish standard' 50 MW plant using synthetic oil at 393 °C are 16.9 €-cent/kWh. Just be replacing the well-established EuroTrough collectors by more cost efficient UltimateTrough collectors, LCoE can be reduced by 9% to 15.4 €-cent/kWh. Making use of economies of scale, i.e. doubling installed plant capacity from 50 MW to 100 MW, and at the same time increasing storage full load hours from 7.5 to 14, another 10% LCoE reduction is accomplished. This can be done today, only available proven technology is required.

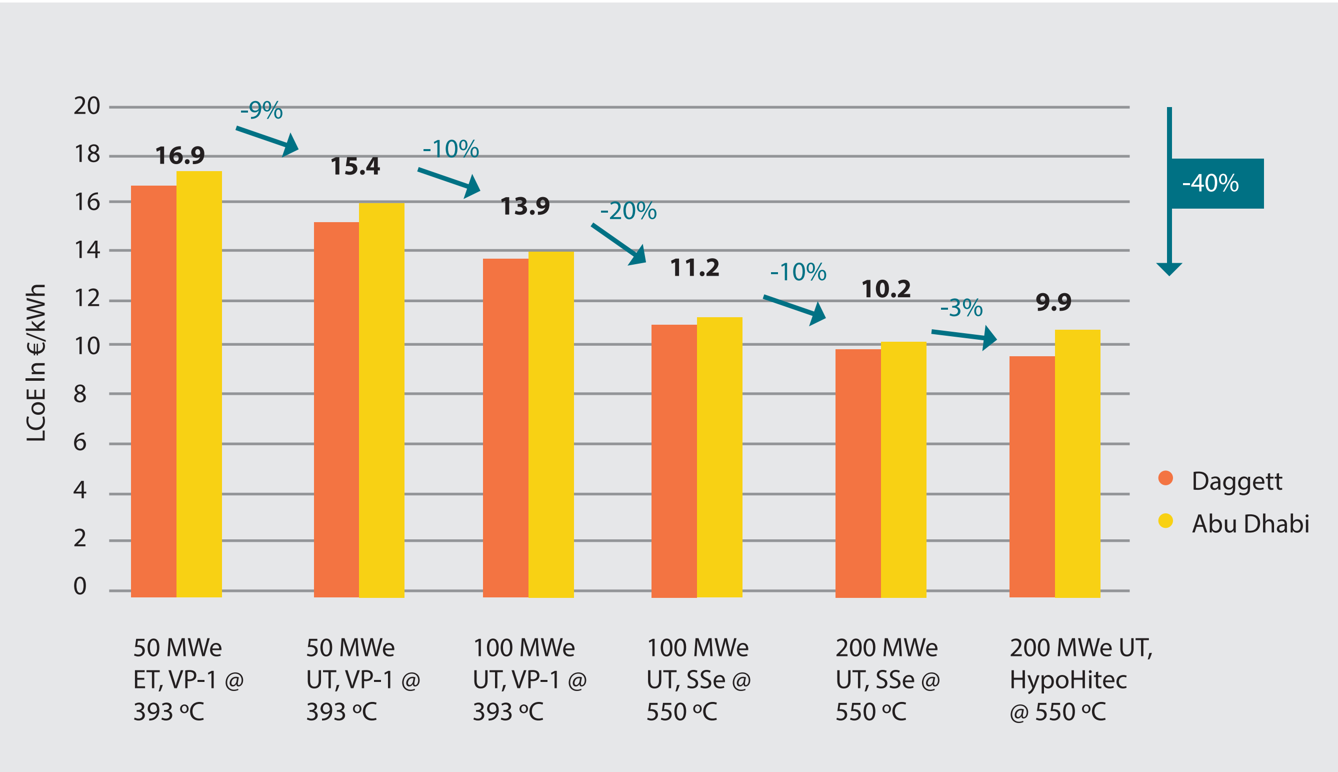


Figure 66 Cost reduction using a cost effciient, large aperture high performance collector 'UltimateTrough', Abbreviations: ET= EuroTrough, UT = Ultimate Trough, SSe = Solar Salt eutectic, HypoHitec = hypothetical Hitec Salt, hypothetcally meaning that the upper temperature limit is extended from 500 °C to 550 °C [46].

In order to further reduce electricity generation cost significantly, a more disruptive change is required: the usage of molten salt both as heat transfer medium in the solar field and as heat storage medium. By doing so, two major improvements can be realized:

Firstly, due to the higher (as compared to synthetic oil) maximum allowable operating temperature of salt as a heat transfer fluid, steam parameters in the power block can be raised to 500 °C or higher, thereby increasing turbine efficiency. The high optical precision of high performance collectors allow higher concentration ratios. Therefore a high efficiency can be maintained, whereas the older generation of collectors suffers from a pronounced reduction in efficiency when increasing operating temperature from roughly 400 °C to 500 °C or higher. Therefore, until recently, such a temperature increase was believed to be unfeasible.

Secondly, heat exchangers between the solar field and the storage system are no longer required; this reduces investment cost and increases efficiency.

Consequently, LCoE can be reduced significantly by using suitable collectors and changing the heat transfer fluid to molten salt.

In the following, a realistic estimate shall be given concerning immediate (~1 year), short-term (~3 years) and mid-term (~5 years) improvements:

4.2 COLLECTOR COMPONENTS

Reflectors. The best performing and most reliable reflectors continue to be glass mirrors. Regarding parabolic trough collectors, reflecting films and composite reflectors (load-carrying substrate plus mirror film/thin glass mirror) are still in their infancy and it is unclear if they will ever play an important role in CSP. Glass reflector panels have seen significant improvement in terms of cost, performance and environmental characteristics in the recent past: Cost of typical 4 mm glass reflectors has dropped from around 30 € to about 15 € per square meter (estimate for 12/2013). It is expected to further drop to about 12 €/m² in the next 1 to 3 years and potentially to about 10 €/m² within 5 years (2012 Euros).

Compared to some years ago, today's reflectors are more environmentally friendly: Due to environmental regulations (in California), lead-free backside coatings have to be used.

In addition, manufacturers will continue their efforts to increase accuracy and reflectivity, i.e. overall performance. Anti-soiling coatings such as duraglare [47] should help to reduce operation and maintenance requirements in general. Moreover, they also target at expanding the areas where CSP plants can be operated economically today by reducing the cleaning effort required.

Absorber tubes (Heat Collecting Elements). Absorber tubes are high-tech components characterized by very high absorption of solar radiation (> 95%) and low thermal losses from infrared radiation ($\varepsilon \leq 10\%$ @ 400 °C) and convection. Future developments will mainly follow two targets: Cost reduction and performance increase.

Cost reduction will be achieved by improved production procedures; it will be forced by increasing competition between manufacturers.

Performance increase here means an increase in absorption and a decrease in emissivity; here no major improvements can be expected any more regarding absorption and emissivity. Developments currently target at increasing maximum allowable operating temperature to 500 °C and above (especially for molten salt applications). In parallel, material scientists develop coatings with extended lifespan.

It can be expected that absorber tubes suitable for operating temperatures of 500 °C and life spans close to those of today's absorber tubes operating at 400 °C will be commercially available by the end of 2014, and that in 3 to 5 years tubes will be on the market for operating temperatures up to 540…550°C.

Metal Support Structure (MSS). Throughout the industry, the trend towards wider collectors is clearly visible (cf. Fig. 67): While the aperture width of practically all parabolic trough collectors installed between 1989 and the present, has been defined by the RP-3 mirror dimensions, i.e. ~5.8 m, more recent designs are characterized by a larger aperture width: The HelioTrough has an aperture width of 6.8 m [44], Gossamer Space Frames' Large Aperture Trough 1 [23] has an aperture width of 7.3 m, the UltimateTrough is characterized by an aperture width of 7.5 m [45].

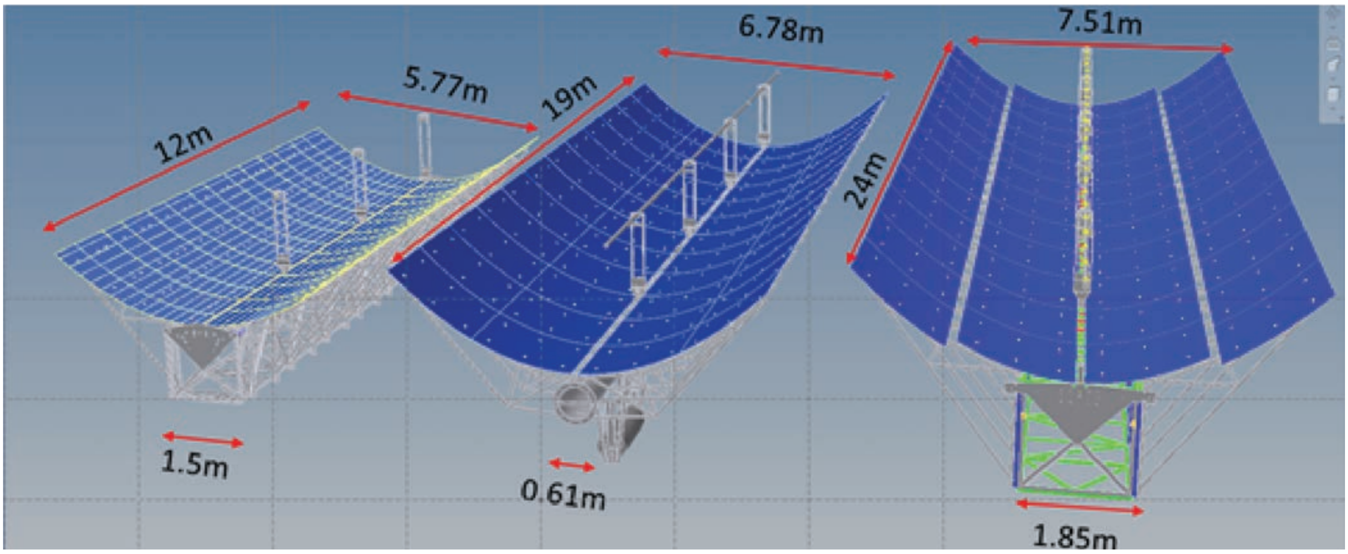


Figure 67: Aperture width and other key dimensions of selected parabolic trough collectors (left: based on RP-3 mirrors, center: RP-4, right: RP-5)

Figure 68: Gossamer Space Frames / 3M Large Aperture Trough 1 (Source: Glenn Reynolds, Gossamer Space Frames)

The idea behind 'going large' is to reduce the number of transport and installation actions per square meter of collector aperture area. In parallel, the number of foundations, drive units, and the effort for cabling etc. is reduced, and therefore are costs. In addition, the number of flexible connections per aperture area is reduced. All this helps to reduce costs. Moreover, optical performance can be increased by reducing end losses, because there are specifically (i.e. per square meter of aperture area) less collector ends.

This effect cannot only be achieved by increasing aperture width, but also by increasing SCE and SCA length. It is not clear and there seems to be no logical explanation why this effects is only exploited to a serious extent by the UltimateTrough collector design with its SCE length of 24 m and an SCA length of 250 m [45], while others increase aperture width, but keep SCE length at the traditional value of 12 m, and SCA length at 100 to 150 m.

Very likely, within the next three years the fraction of large(r) aperture collectors used in commercial projects will increase to one quarter, maybe one third. Still, mostly due to 'copy and paste' in tender specifications, and because of the availability of components and manufacturing equipment, the majority of plants will still be realized using collectors with the 25 year old RP-3 geometry. Nevertheless, it is expected that within five years from today a significant portion of collectors being installed will be with a larger aperture than 5.8 m.

Drives and Control. Various drive concepts have been conceived and tested until today. In the past years, most trough designers seem to agree that hydraulic drives are the most cost efficient solution. A typical configuration is shown in Fig. 69. The hydraulic drive system, consisting of two hydraulic cylinders and a hydraulic power unit, turns the collector and holds it in position, when its not turning.

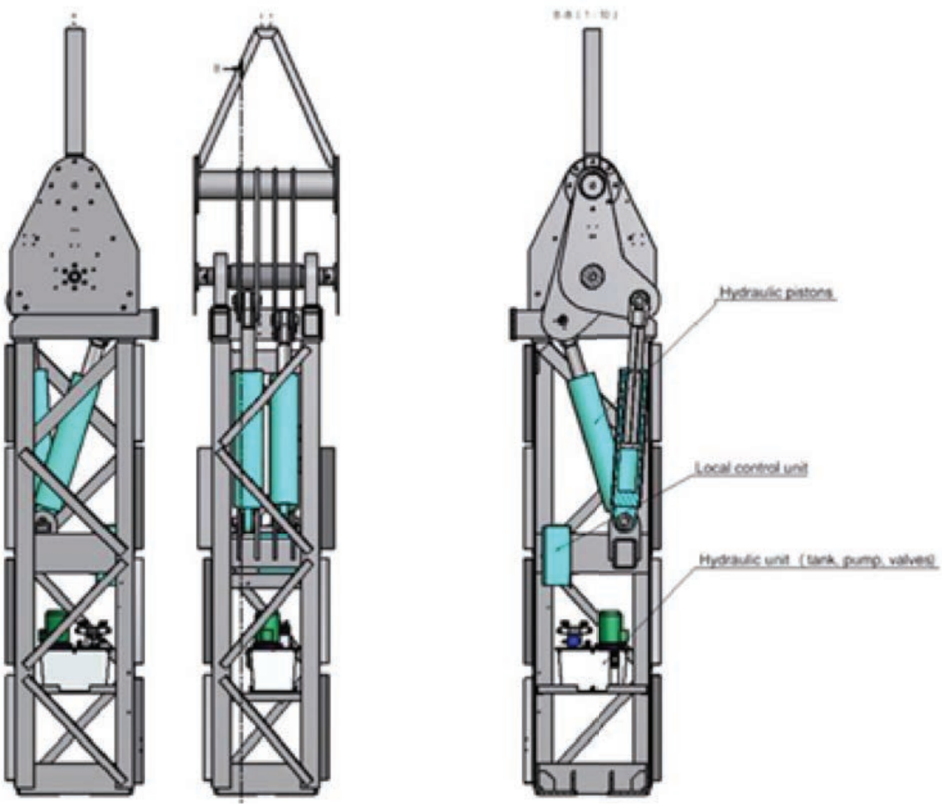


Figure 69: Schematic of typical drive pylon with two hydraulic cylinders (in blue)

4.3 COLLECTOR DESIGN

The general development that can be observed is to increase aperture width (practically all major players) and increase collector length (only some technology developers), see above.

All trough technology developers target assembly and installation cost reduction (e.g. [23], [48], [49]). Some see the usage of aluminum (space frame) structures as the best way towards cost efficiency, and claim that jigs are not necessarily required for such structures, and that a high precision can be reached even through jigless assembly using high precision aluminum members and nodes. Others state that jigs are the most cost efficient way to build parabolic trough collectors, because they allow for high shape accuracy and cost very little if used for a large number of collector elements, as it is the case when constructing a power plant.

A similar competition can be observed between proponents of aluminum and galvanized steel. Today it cannot be foreseen with 100% reliability, which material will eventually be the winner, but today a vast majority of collectors is built from galvanized steel using jigs, and currently there are no signs that this will change.

4.4 SOLAR FIELD / PLANT CONCEPTS

Today practically all commercial plants use synthetic oil as heat transfer fluid. Direct steam generation was seen as the logical step towards cost reduction for a longer period in the past, starting in the 1990ies. Today, this is not the case anymore, because storage integration is difficult, expensive and inefficient with direct steam generation plants. Instead, molten salt as both heat transfer and thermal energy storage medium is in the focus of all major players today.

Because of the rapid reduction of photovoltaic systems, solar thermal power plants can hardly compete on a cost per kilowatt-hour base alone. Instead, their advantage lies in the fact that they deliver dispatchable power, i.e. power reliably when it is needed, not only when the sun shines. Therefore, the future market for parabolic trough power plants will be dispatchable power, i.e. plants with storage.

Trough systems using molten salt as HTF will ease storage integration and lead to further cost reduction. Cost-effective precise trough collectors are prerequisite for cost reductions for installation, operation and maintenance. The latest collector developments are a major step towards that goal. Still, further improvements and cost reductions are possible and will be implemented in the next generations of plants, moving along the learning curve and making use of lessons learned from operating the existing plants. The straightforward integration of cost effective thermal energy storage systems make CSP plants an increasingly important building block for our sustainable future electricity supply.

5 APPENDIX I: KEY CSP COMPANIES

In the following paragraph 10 main EPC (Engineering, Procurement and Construction) companies, collector developer and component supplier will be presented.

Company Name	Type	Field of activity	Workforce Total	Annual turnover energy (Million Euros)	Total annual turnover (Million Euros)	Total installed Capacity until 2012	Track record for CSP power plants
Abengoa Solar, Spain [50]	EPC, Collector developer, Business Area: Energy and Environment	Traditional engineering and construction, concession-type infrastructures, industrial production	2010: 480 2011: 771 2012: 1,247	2011: 345	2010: 168.2 2011: 345.4 2012: 688.2	743MW in commercial operation 9MW under construction	**Spain** Solucar Complex Solnova 1 Solnova 3 Solnova 4 PS10 PS20 Écija Solar Complex El Carpio Solar Complex Castilla-La Mancha Solar Complex Extremadura Solar Complex ISCC Hassi-R'Mel Extremadura Solar Complex United Arab Emirates Shams-1, Abu Dhabi **United States** Solana, Arizona Mojave Solar Project **California** South Africa KaXu Solar One Khi Solar One

Company Name	Type	Field of activity	Workforce Total	Annual turnover energy (Million Euros)	Total annual turnover (Million Euros)	Total installed Capacity until 2012	Track record for CSP power plants
Cobra Energía, Spain [51]	EPC	Thermoelectricity: Promotion and development, turnkey construction, and operation and maintenance of solar thermal power plantsdevelopment, turnkey construction, and operation and maintenance of solar thermal power plants	28,000	n.a.	2012: 4,000	500 MW	Andasol-1, Spain Andasol-2, Spain Extresol-1, Spain Extresol-2, Spain Extresol-3, Spain Manchasol-1, Spain Manchasol-2, Spain Valle-1, Spain Valle-2, Spain Gemasolar (Solar 3). Spain Crescent Dunes, USA
Lauren CCL, India [52]	EPC	engineering, procurement, management and construction services for thermal solar power facilities in India	n.a.	n.a.	n.a.	n.a.	Godawari Green Energy, India Cargo Power and Infrastructure, India 75 MW Solar Thermal PP, Florida Power & Light 72 MW Solar Thermal Power Generating Facility, Solargenix Energy, Nevada
Elecnor, Spain [53]	EPC	designing and constructing large-scale photovoltaic installations; design, supply, construction, start-up, operation and maintenance of thermoelectric solar power plants	12,000	n.a.	2011: 1,325		Astexol-2, Spain Aste-1 A, Spain Aste-1B, Spain

Company Name	Type	Field of activity	Workforce Total	Annual turnover energy (Million Euros)	Total annual turnover (Million Euros)	Total installed Capacity until 2012	Track record for CSP power plants
Grupo TSK, Spain [54]	EPC, O&M company Spain	Mining and Handling, Power, Industry, Electrical & Control Infrastructures, Solar PV, Environment, Oil & Gas, I.T.	752	58% of total sales	Sales: 2010: 301 2011: 348 2012: 403	260 MW	La Dehesa, Spain La Florida, Spain Noor I, Morocco
Acciona Energy, Spain [55]	EPC, Spain	development and management of infrastructure, renewable energy, water and services	32,905	2011:1,650 2012:2,107 2013: 1,627 (January – September)	2013: 7,016	20,379 GWh (Wind and solar Thermal)	Consol Orellana, Spain Fort Irwin, USA La Risca, Spain Majadas, Spain Morón, Spain Olivenza I, Spain Palma del Rio I Palma del Rio II
JGC, Japan [56]	EPC, O&M, Japan	Engineering Services, Energy and Chemical Business, Industry and Society, Investment/ Service Business, Planning and Management	6,721	n.a.	Net sales: 2011: 2,5 2012: 3,2 2013: 3,2	n.a.	n.a.
Larsen Toubro, India [57]	EPC for Solar PV, CSP, Solar Thermal applications and Rooftop & micro grid solutions	Hydrocarbon, Heavy Engineering, L&T Construction, Power, Electrical & Automation, Machinery & Industrial Products, Information Technology, Financial Services, Shipbuilding, Railway Projects	40,000	333	2007-08: 356,93 Crore 2008-09: 489,96 Crore 2009-10: 530,40 Crore 2010-11: 628,07 Crore 2011-12: 777,58 Crore	Under construction: 125 MW Linear Fresnel	Qualified for 50 MW CSP Parabolic Trough plant with 10 hr storage at Kuwait

6 APPENDIX II: SELECTED COMPONENT SUPPLIERS

Company Name	Type, Field of activity	Track record for parabolic trough power plants	Add. Information
Schott Solar, Germany [28]	International technology group in the area of specialty glass and materials	- 3 GW installed base (out of 4 GW total) - More than 50 projects supplied around the globe - More than 1 Million receivers Delivered	
Senior Berghöfer, Germany [34]	Developer of metal hoses, expansion joints and bellows for land vehicles and engines, Power Generation and industrial technology. Supplier of Flexible connections to the heat collectors of parabolic trough collectors, linear Fresnel systems		
Rioglass, US Arizona [60]	Manufacturer of parabolic mirrors for solar fields	Andasol 3, Astexol2, Cordoba 2, Ecija 1, Ecija 2, Ibersol, La Dehesa, La Florida, Majadas, Palma del Río Pouertollano, Solnova 1, Solnova 3, Solnova IV Cameo, Martin Solar, SEGS 1-VIII, HassiR'mel, Ain Beni Mathar, Haifa	Production capacity of Trough mirrors: 900.000 units / year (Phase1) Products: Reflectors of all sizes (LS2, LS3, LS4 & custom designs) and for any solar applications.
Hawe Hydraulic, Germany [61]	Leading manufacturer of technologically advanced, high-quality hydraulic components and systems. Hydraulic solutions for tracking systems in solar power plants		
Flabeg, Germany [62]	Manufacturing of: automotive mirrors, technical glass, parabolic mirrors for solar thermal power plants Technology Development and Engineering for solar thermal power plants	Manufacturing of mirrors for over 30 parabolic trough power plants all over the world	6,5 Million pieces of mirrors in running CSP power plants, 16,5 million m^2 of installed mirrors mainly in parabolic trough power plants and other CSP power plants

7 APPENDIX III: SELECTED TECHNOLOGY DEVELOPERS

Company Name	Field of activity	Add. Information
Gossamer Spaceframes[23]	Offering large commercial production of solar troughs, Project Management, project team integration, manufacturing technical support, field services	6 major utility-scale CSP (Concentrated Solar Power) plants deployed - Nevada Solar One – 50 MW - Martin County (FPL) – 75 MW - La Risca, Spain – 50 MW - Majadas, Spain – 50 MW - Palma Del Rio, Spain – 50 megawatt - Palma Del Rio, Spain – 25 megawatt
TSK Flagsol, Germany [63]	EPC contractor and technology developer Construction of solar fields and turn-key parabolic trough power plants using their own technology, consultancy services and offering of products and components of their technology.	Track record: Andasol 1, 2, 3 Spain Kuraymat ISCC, Egypt, Los Arenales, Spain Samca 1, 2, Spain La Africana, Córdoba Puerto Errado, Spain Bokpoort, South Africa Quarzazate, Morocco
Skyfuel, USA [19]	Design of solar thermal power technology for utility-grade electricity generation and industrial applications	Technology: SkyTrough concentrator
sbp sonne gmbh, Germany [64]	Consulting engineers and technology developer Planning, design, construction, optimization, assembly and commissioning of CSP systems	Over 30 years of experience. Collector developments: Ultimate Trough and Euro Trough (successfully implemented in many power plants all over the world with a total output of 350 MW) Planning from prototype to series production. Track record of more than 10 Parabolic trough power plants in the US, India, Spain and Egypt Godawari GGEL Power Plant, India Power plant Morón, Spain Solar combined Power Plant Kuraymat, Egypt Astexol2, Spain Andasol 1, 2, 3 Spain
SENER, Spain [65]	EPC contractor and technology developer Development of solar thermal power plants, as well as cycle electrical, liquefied natural gas regasification, nuclear energy, biofuel, refineries, chemical, petrochemical and plastics plants	Technology: SENER trough Track record: Parabolic Trough Power Plant, Villena Casablanca Parabolic Trough Plant, Spain Orellana Parabolic Trough Plant, Spain ASTE 1A &1B, Spain La Africana, Spain SoLUZ Guzman, Spain Valle 1, Valle 2, Spain Andasol 1, 2, Spain

Engineering and Steel Construction

Company Name	Type	Field of activity	Track record for parabolic trough power plants	Add. Information
Ingemetal	Engineering and Steel Constructor	Apart from Energy, Steel Structures, Roofs and Façade Cladding, Curtain Walls and Laser Metrology services	- Andasol 1, 2006-2008, in Spain (ACS Cobra as developer & Cobra-Sener as EPC) - Andasol 2, 2008-2008, in Spain (ACS Cobra as developer & Cobra-Sener as EPC) - Andasol 3, 2009-2010, in Spain (Solar Milennium as developer & Duro Felguera-MAN Solar Milennium-Flagsol as EPC) - La Florida, 2008-2009, in Spain (Samca as developer & EPC) - La Dehesa, 2009-2010, in Spain (Samca as developer & EPC) - Astexol 2, 2010-2011, in Spain (Elecnor as developer & EPC) - Godawari, 2012-2013, in India (Godawari Green Energy Limited as developer & Lauren as EPC)	Workforce: 300 people Workforce in the CSP sector: 220 (in India and Spain) Total installed capacity until 2012: + 350 MW

Fig. 70 below gives an overview on all parabolic trough power plants, which are currently planned, in operation or construction, with regard to capacity and responsible EPC company.

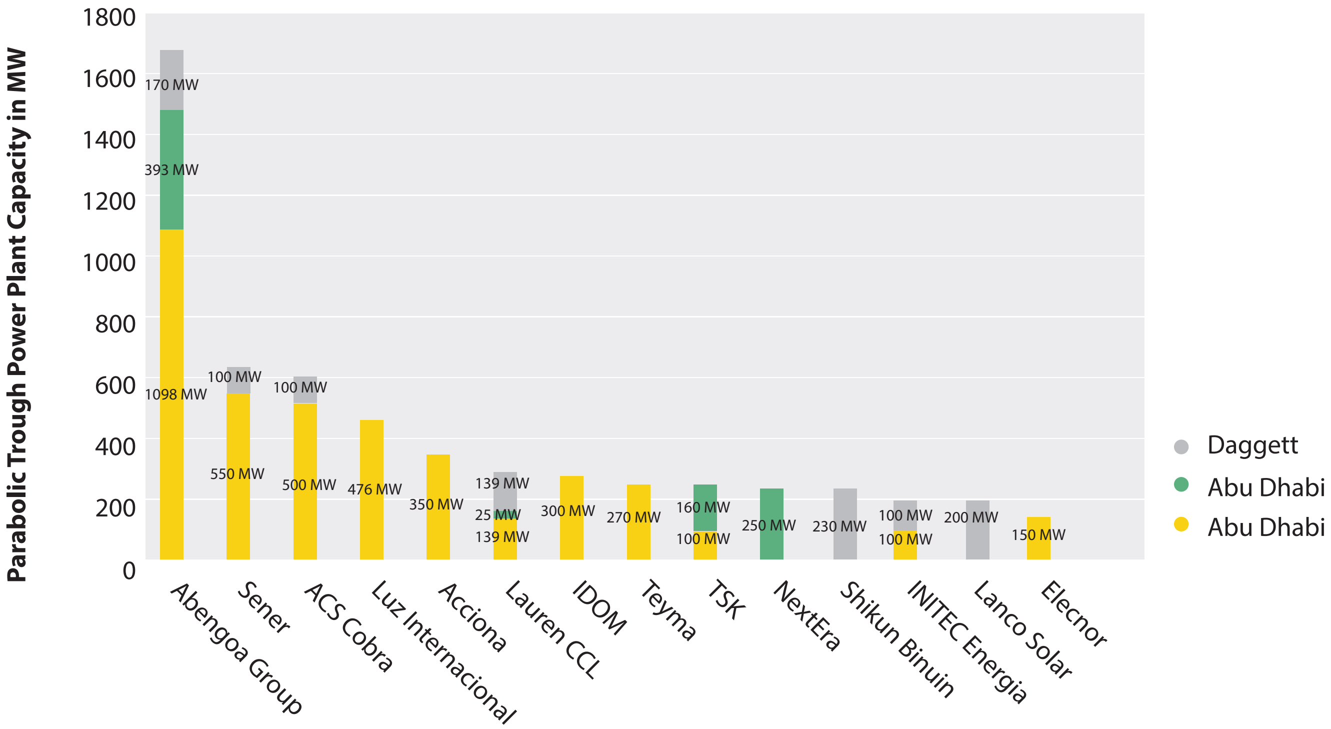


Figure 70: Overview on parabolic trough power plants EPC contractors

8 APPENDIX IV – LOCAL SUPPLY OPTIONS FOR PARABOLIC TROUGH COLLECTOR FIELD

This appendix gives a short specification of the main components necessary for a CSP trough collector field. The description of specific characteristic requirements and necessary manufacturing skills should facilitate the assessment of manufacturing possibilities in Brazil. A lifetime of at least 25 years in outdoor conditions is a common condition to all below listed components.

Collector Structure

Challenge: high mechanical stiffness required regarding bending and torsion, low weight, easy assembly, low cost, high precision

Component/part	Key raw material	Specific requirements	Skill requirements
foundation	concrete (pile or slab)	precise position of anchor bolts	basic technical equipment
pylon	standard steel, standard rolled sections, etc.	good corrosion protection	basic technical equipment
frame, cantilever arms	standard steel, slender hollow sections	narrow tolerances, good corrosion protection	basic technical equipment
torque tube	standard steel, welded tube section	narrow tolerances regarding straightness and roundness	tube welding equipment; experience in tube welding required

Mirror

Challenge: high reflectivity (>94%), zero to low degradation, high precision.

Component/part	Key raw material	Specific requirements	Skill requirements
glass	Low iron ('solar white') glass (tempered or annealed)	high reflectivity and durability	glass technology
coatings	silver coating and several protective coatings of copper and lacquer (lead free)	protection must be UV resistant and reliable	mirror coating technology
pads	ceramic or polymer	high UV resistance	ceramic / polymer technology

Receiver

Challenge: high efficiency (low heat losses), high temperatures (400 - 500°C)

Component/part	Key raw material	Specific requirements	Skill requirements
coated steel tube	stainless steel, coating (about 4 to 5 m length)	seamless, polished and coated with selective coating, high temperature resistance of >400 °C	high technical standard for coating
glass tube	glass	high light transmission, vaporized	high technical standard
gaskets and expansion compensators	stainless steel and others	ensure vacuum, compensate thermal expansion difference of glass and steel	high technical standard

Drive System

Challenge: high tracking accuracy, low cost, high active and passive forces.

Component/part	Key raw material	Specific requirements	Skill requirements
drives (1 axes)	steel, two hydraulic pistons with pump driven by electric motor	high precision, high durability	precise and high quality manufacturing
control	electronics, sensors	high precision, reliability	
connection	cables	low cost, outdoor use, high UV resistance	standard cable equipment

Oil to Water / Steam Heat Exchangers

Challenge: More start-ups or trips compared to conventional power plants.

Component/part	Key raw material	Specific requirements	Skill requirements
heat exchanger	stainless steel	many temperature cycles > fatigue	high quality manufacturing; high experience

Oil to Salt Heat Exchangers

Challenge: More start-ups or trips compared to conventional power plants.

Component/part	Key raw material	Specific requirements	Skill requirements
heat exchanger	stainless steel	many temperature cycles > fatigue; aggressive components > high chemical resistance; high leak tightness	high quality manufacturing; high experience

Oil Pumps

Challenge: high temperatures (400 °C)

Component/part	Key raw material	Specific requirements	Skill requirements
oil pumps	stainless steel	variable frequency drives are required to adapt pump flow to field requirements	high quality manufacturing; high experience

Heat Transfer Fluid

Challenge: low freezing point; high working temperature; high thermal stability; high heat capacity

Component/part	Key raw material	Specific requirements	Skill requirements
synthetic oil	Dowtherm A or Therminol VP1 type (or similar)	no decomposition before 393 °C (at 11 bar); freezing point at 12 °C	
salt	nitrate mixture	no decomposition before 550 °C; freezing point at 100 °C to 230°C	

Thermal Storage

Challenge: thermal insulation; drainable

Component/part	Key raw material	Specific requirements	Skill requirements
storage tanks	stainless steel; insulation	high working temperatures (290 °C to 550 °C); good thermal insulation	experience in vessel technology

Header Piping

Challenge: thermal insulation; drainable

Component/part	Key raw material	Specific requirements	Skill requirements
header piping	stainless steel; insulation	high working temperatures (290° to 550°C); good thermal insulation, high thermal expansion	basic technical equipment

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