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EUROTROUGH - Parabolic Trough Collector Developed for Cost Efficient Solar Power Generation

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Abstract - The high-performance EuroTrough parabolic trough collector models ET100 and ET150 have been developed for the utility scale generation of solar steam for process heat applications and solar power generation. With corresponding receiver tubes they can be used in combination with various heat transfer fluids in large solar fields. With an optical concentration of 82:1 operating temperatures over 500°C may be reached. The ET100 and ET150 structure geometry has included wind channel and finite element method validation and is compatible with the standard receiver tubes and mirror panels of the market. The loop and field concept is also fully compatible with the proven solar field technology of the successful Solar Electric Generating Systems (SEGS) in California and can be integrated to field sizes for up to 200 MW_{el} solar plants. The collector modules have been fully qualified in the years 2000 – 2002 with a synthetic heat transfer fluid for 395°C operation at the Plataforma Solar in Almeria with independent performance test certificates from the research laboratories. 14% solar field cost reduction are anticipated due to weight reduction and collector extension to 150 meters. A 50 MW solar power plant with 549 000 m^2 of EuroTrough collectors and 9h-thermal storage is projected for South Spain.

1. Technical Features

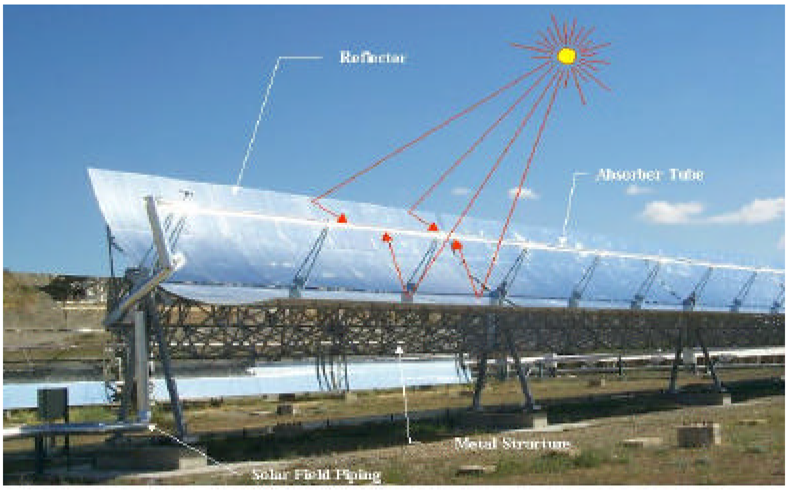


Figure 1: Working Principle of the EuroTrough collector

Figure 1 shows the working principle of the EUROTROUGH collector at the Plataforma Solar. By tracking the sun from sunrise to sunset, the parabolic EuroTrough collectors concentrate the sun's radiation with their parabolic mirror facets on the absorber tubes along their focal line. Through these absorber tube circulates a heat transfer fluid (HTF), usually synthetic oil, which is heated to a temperature of nearly 400°C.

EuroTrough Model	**ET100**	**ET150**
Focal Length	1.71 m	1.71 m
Absorber Radius	3.5 cm	3.5 cm
Aperture Width	5.77 m	5.77 m
Aperture Area	545 m^2	817.5 m^2
Collector Length	99.5 m	148.5 m
Number of Modules per Drive	8	12
Number of Glass Facets	224	336
Number of Absorber Tubes (4.1 m)	24	36
Mirror reflectivity	94%	94%
Weight of steel structure and pylons, per m^2 aperture area	19.0 kg	18.5 kg

Table 1: Main characteristic parameters of EuroTrough 100 m and 150 m

The EuroTrough collector models are made up of identical 12 m long collector modules. Each module comprises 28 parabolic mirror panels - 7 along the horizontal axis between pylons and 4 in a vertical cross-section. Each mirror is supported on the structure at four points on its backside. This permits the glass to bend within the range of its flexibility without effect on the focal point. The 100 m long ET100 has 8 collector modules and an aperture area of 545 m^2, the 150 m long ET150 has 12 collector modules and an aperture area of 817.5 m^2.
Detailed wind tunnel tests have been conducted for obtaining a reliable database for the expected wind loads at different locations in the collector field. Bending and torsion forces have been determined in these experiments. Horizontal forces and pitching moments have been evaluated for different wind speed and direction, different collector positions in the field and various elevations of the collector.

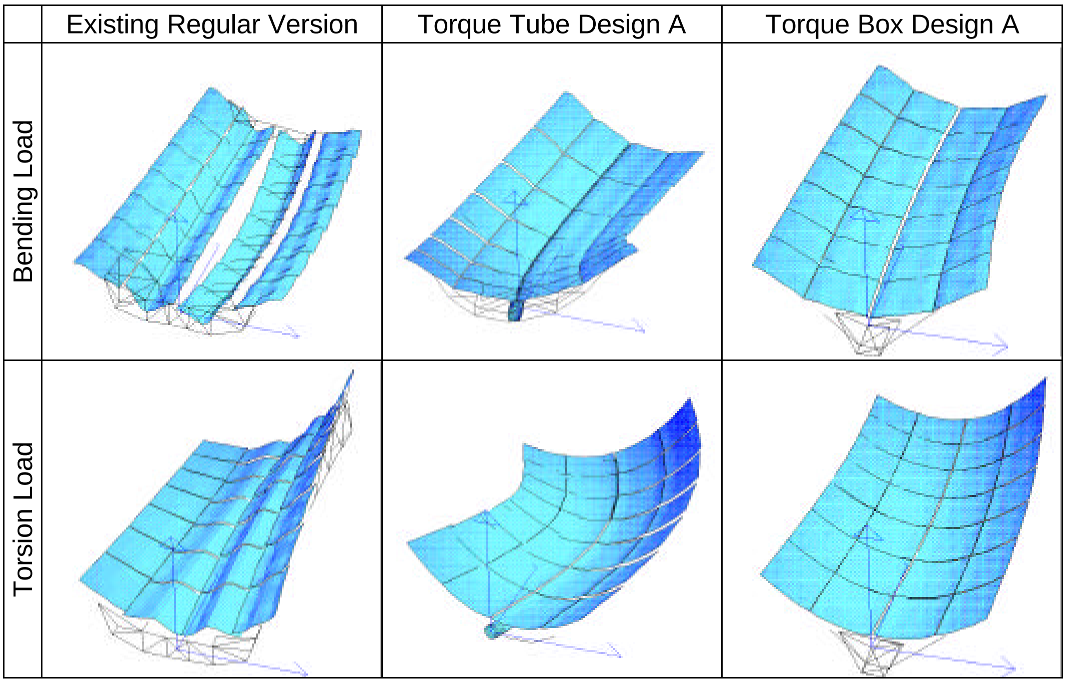


Figure 2: Concentrator deformation analysis for different support structures

Detailed FEM investigations (see Figure 2) on the structural behaviour under various load cases (dead load, wind loads for a range of pitching angles of the collector and wind directions) for alternate designs, complex computer modelling and ray tracing were performed to obtain the best possible relationship of optical accuracy and collector cost.

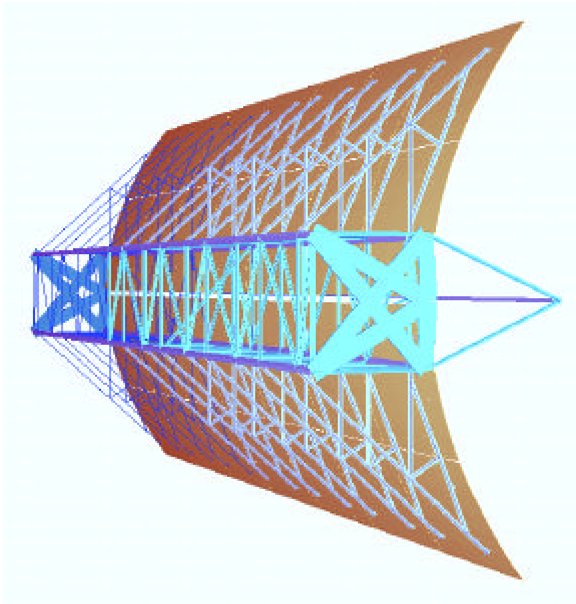


Figure 3: Computer Model of the EuroTrough Collector with Torque-Box Design

Based on these studies a so-called torque-box design has been selected for the EuroTrough, with less weight and less deformations of the collector structure due to dead weight and wind loading than the reference designs (LS-2 torque tube or the LS-3 V-truss design, both commercial in the Californian plants). This reduces torsion and bending of the structure during operation and results in increased optical performance and wind resistance. The weight of the steel structure has been reduced about 14% as compared to the available design of the LS-3 collector.

The central element of the box design is a 12-m long steel space-frame structure having a squared cross section that holds the support arms for the parabolic mirror facets. The torque box is built out of only 4 different steel parts. This leads to easy manufacturing, and decreases required efforts and thus cost for assembling on site. Transportation volume has been optimized for maximum packing. The structural deformation of the new design is considerably less than in the previous design (LS-3), which results in a better performance of the collector. Thus the spillage during operation can be reduced by approximately 2-10 percentage points.

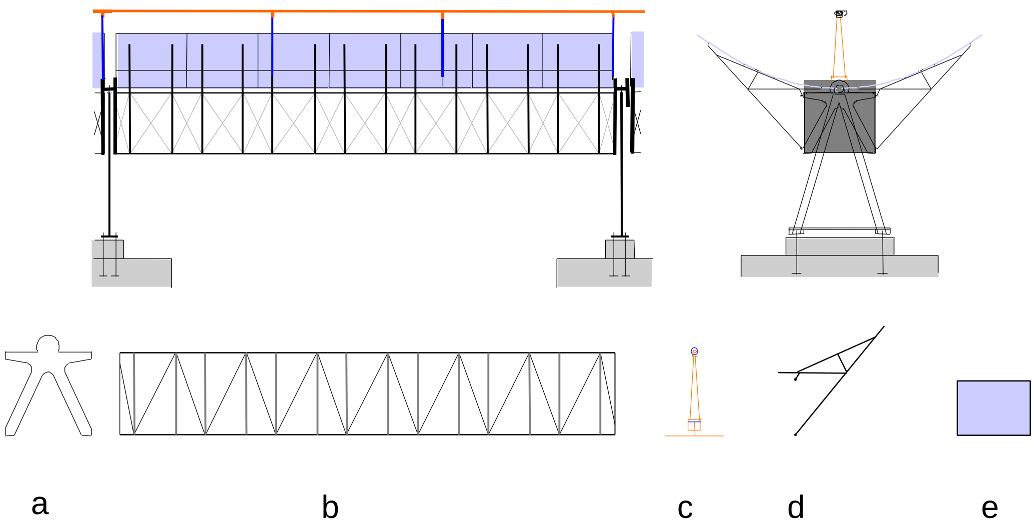


Figure 4: EuroTrough collector element consisting out of (a) 2 endplates; (b) 4 simple steel frames screwed to a torque box; (c) 3 absorber tube supports; (d) 28 cantilever arms and (e) 28 mirror facets.

The design utilizes mirror supports that make use of the glass facets as static structural elements, but at the same time reduce the forces on the glass sheets by a factor of three. This promises less glass

breakage with the highest wind speeds. Absorber tube supports were designed such to reduce the breakage risk and to ease mirror cleaning in comparison to the LS-3 collector.
The accuracy of the concentrator is achieved by a combination of prefabrication with jig mounting on site. The majority of the structural parts are produced with steel construction tolerances. The accuracy for the mirror supports is introduced with the glass brackets on each of the cantilever arms. This concept allows minimum assembly manpower and cost in series fabrication of solar fields.
The ET100 and ET150 are tracked with the sun during operation along their long axis with a hydraulic drive. The drive system consists out of two hydraulic cylinders mounted on the central drive pylon. From a control box mounted on the drive pylon signal and power lines lead to the hydraulic unit, the rotational encoder, limit switches and temperature sensors.

The tracking system developed for the ET100 and ET150 on the Plataforma Solar is based on 'virtual' tracking. The traditional sun-tracking unit with sensors that detect the position of the sun has been replaced by a system based on calculation of the sun position using a mathematical algorithm [2]. The unit is implemented in EuroTrough with a 13-bit optical angular encoder (resolution of 0.8 mrad) mechanically coupled to the rotation axis of the collector. Comparing both sun and collector axes positions by an electronic device, an order is sent to the drive system, inducing tracking. The latest version of the solar coordinates calculation algorithm was checked against the Multiyear Interactive Computer Almanac (MICA), a software product of the United States Naval Observatory. Errors in longitude and/or latitude of the site below 10 km do not provoke a significant positioning error, if the parabolic trough collectors are correctly aligned.

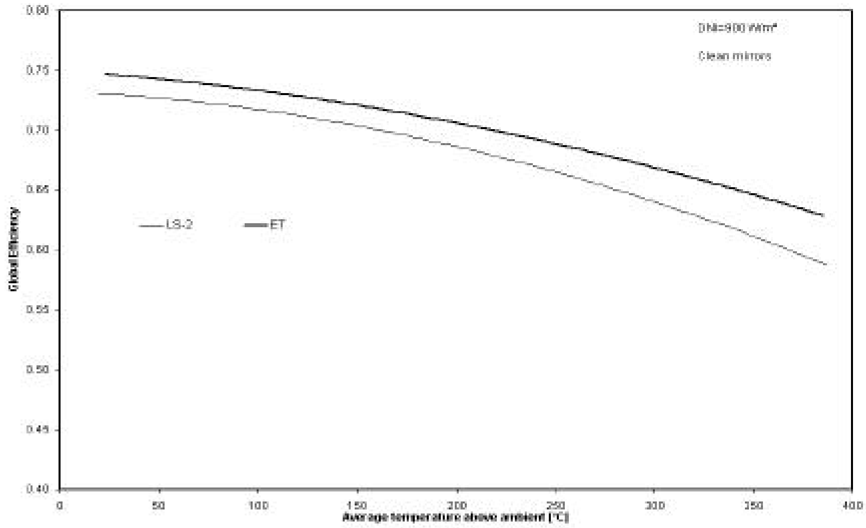
Following cost reduction potentials have been exploited:

1. Cost reduction by simplification of the design:
   less different profiles, parts, better transportation; assembly concept; cost reduction by weight reduction of the structure; frame work structure, closed profiles, corrosion protection; finite element method for structural design calculations; wind analyses for proper definition of the load cases
2. Cost reduction by improvement of the optical performance of the collector:
   rigid support structure --> frame work torque box; manufacturing, assembly accuracy
3. Cost reduction achieved in additional steps: possible tilt of the collector and extension of collector length per drive unit (ET150).

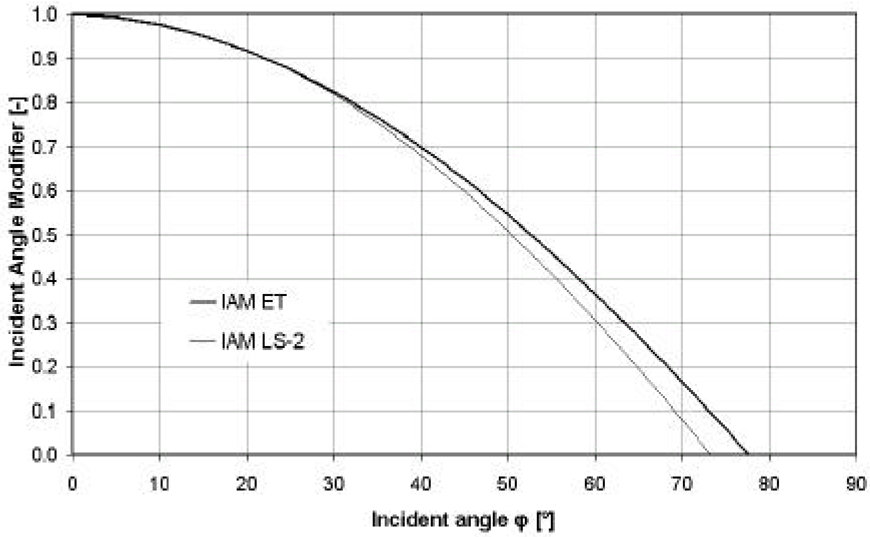
The anticipated overall cost reduction for the solar field is 14% for ET150 collectors. Additional reduction of solar electricity cost will be achieved by the higher annual performance due to improved optical parameters.

2. Performance

Tests were carried out and evaluated on thermal performance and structural torsion under external load. The EuroTrough collector showed a performance of 3 % points higher than LS-2 reported by Sandia, see Figure 5.
Because of the fact that the efficiency definitions used by Sandia for the LS-2 collector evaluation [5] are the same as used for the EuroTrough, both collector types can be compared directly. The measured specific thermal losses of the EuroTrough and the LS-2 collector are almost identical, which is explained by the use of the same heat collection element as absorber (Solel HCE tubes with Cermet coating). That leads to a similar thermal efficiency of both collectors. The EuroTrough collector behavior for incident angles of more than 30° is more efficient than the LS-2 collector. This is due to the larger collector module, higher geometric precision of the parabola, and less shading due to improved absorber support design.
Collector torsion under load was analyzed from the measurements of the angular encoders of each collector pylon.
A test with photogrammetric surface analysis has been performed. Its results served for detailed 3-dimensional insight in the reflector and support structure properties and improvements towards higher collector efficiency.



(a)



(b)

Figure 5: Global Collector Efficiency (a) and Incident Angle Modifier (b) for the EUROTROUGH collector (upper line) and the LS-2 reference measurements (Sandia, USA), both using previous version of Solel HCE absorber tubes, for clean mirrors, reference area 4 x 11.98 x 5.77 m^2, and DNI = 900 W/m^2.

The new model of absorber tube – the UVAC (Universal vacuum collector, SOLEL), has the same external size and shape as the previous model (HCE), but higher performance and better durability. The following product improvements were achieved:

1. Coefficients of absorptivity α and emissivity ε are improved to give additional thermal annual output of up to 20% (depending on site conditions).
2. The original selective coating was designed to be stable at high temperature and in vacuum but the stability at exposed environment (air & humidity) was relatively limited. The applied UVAC selective coating is designed to work at vacuum and exposed outdoor conditions, with no oxidation or oxide deposit on the glass tubes. Operating temperature at exposed environment (air) is 400°C.
3. A new solar radiation shield set was designed in such a way, that it shields the glass to metal connection zone and the bellow connections, maintaining the fixed relative position in spite of the axial displacement of the tube during heat up. The design specification demands of the shield set are to protect the glass-to-metal connection even at extremely low radiation angles of the sun, of both direct and reflected sunrays, while it interferes as little as possible with the effective collecting area of the UVAC, so as not to deteriorate the overall efficiency of the solar system.

Possible heat transfer fluids are ranging from the proven synthetic oils to silicon oil, water/steam and molten salts.

3. Solar Field Design with EuroTrough Collectors

The ET100 and ET150 EuroTrough collector models can be serially connected with flexible ball joints to loops. Each loop can consist of six to eight ET100 EuroTrough collectors or four to six ET150 EuroTrough collectors, depending on the site conditions and solar field size.

Figure 6 shows a layout example of a solar field with the 100 m long ET100 EuroTrough collectors. The two collector loops located at the outside borders of the solar field are reinforced, so-called "strong" ET100 models to withstand the higher wind loads; the inner ET100 loops are of regular type.

Cold HTF flows from the power block area into a cold heat transfer fluid (HTF) header that distributes it to the parallel loops of EuroTroughs in the solar field. Two adjacent rows of collectors are connected by a crossover pipe near the edge of the solar field and form a loop. HTF is heated in the loop and enters the hot header, which returns hot HTF from all loops to the Power Block area.

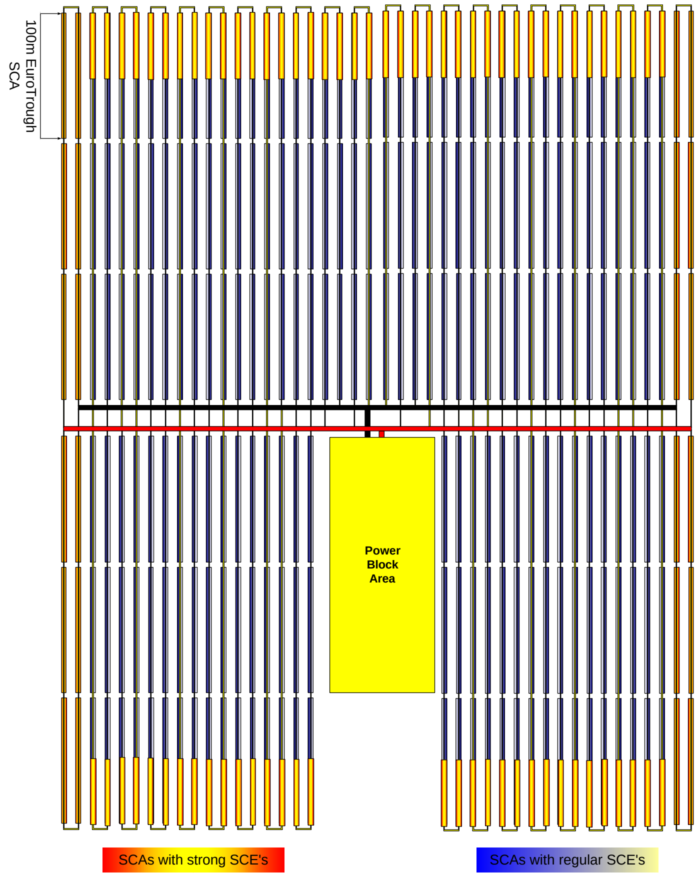


Figure 6: Principle layout of solar field with strong and regular 100m EuroTrough collectors

4. EuroTrough Costs and Market Perspectives

The industrial EuroTrough partners are prepared to offer solar fields with the EuroTrough collectors ET100 and ET150 on a turn-key basis to utilities, IPP developers and process heat users; they have been prequalified with EuroTrough solar field offers for the Integrated Solar Combined Cycle projects in Mathania (India) and Kuraymat (Egypt). EuroTrough solar field cost depends on field size and specific site. For a first of ET150 solar field with at least 500 000 m^2 in Southern Spain, the EuroTrough partners count with solar field cost of 206 €/m² including HTF system and installation.

Under the contract of the Solar Millennium AG of Germany, the EuroTrough industrial partners are now engineering the Andasol project, a 50 MW solar only plant with 549 360 m^2 EuroTrough solar field and 9 hours of storage for implementation in Southern Spain under the framework of the Royal Decree 2818 and its expected premium for solar thermal power. With a measured annual direct normal irradiation of 2200 kWh/a, this field of ET150 EuroTrough collectors will annually supply 594 312 MWh_{th}/a of solar steam to a Rankine cycle of 38% gross annual efficiency, which feeds 181 700 MWh_e/a of net solar electricity to the grid. The cost of the EPC contract (without land and without contingencies) amount to

181 M€. With an expected lifetime of 25 years, an annual depreciation of 6.7%, an annual discount rate of 9.0%, an annual insurance rate of 1.0% and an annual income tax rate of 35%, the Levelized Electricity Costs according to the IEA method are 0.15 €/kWh for this project.

5. EUROTROUGH Consortium

Mediterranean Solar Process heat applications of the EuroTrough technology have been investigated by the independent consultant Fichtner Solar GmbH (Germany) and the research laboratory CRES (Greece). Power equipment costs have been verified by the Spanish utility partner Iberdrola. The EuroTrough technology and engineering is fully backed by the industrial supply partners of the EuroTrough consortium, i.e. the companies Abengoa/Inabensa (Spain), Flabeg Solar International GmbH (Germany) and Schlaich Bergermann & Partner (Germany). Solel (Israel) contribute the high efficient UVAC absorber tubes for the ET100 and ET150 modules at the PSA. Ciemat (Spain) and DLR (Germany/Spain) support the development mainly with their experience on collector development and testing on PSA. The development and qualification testing of the EuroTrough was financially supported by the European Commission within the 4th and 5th Framework Programs under contracts JOR3-CT98-0231 and ERK6-CT-1999-00018. The development was further supported by the Spanish and German Governments to Ciemat and DLR respectively.

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