Technische Hochschule Wildau
Technical University of Applied Sciences

Annex B

Supplement of Master Thesis

Parabolic Trough Collectors for Large Scale Application

Conventional and Innovative Concepts

Thesis Title (german):	Konzentrierende Solarenergie: Vergleich und Bewertung von innovativen Parabolrinnenkollektor-Konzepten für die Anwendung im großen Maßstab
Thesis Title:	Concentrating Solar Power: A comparison and evaluation of innovative parabolic trough collector concepts for large scale application

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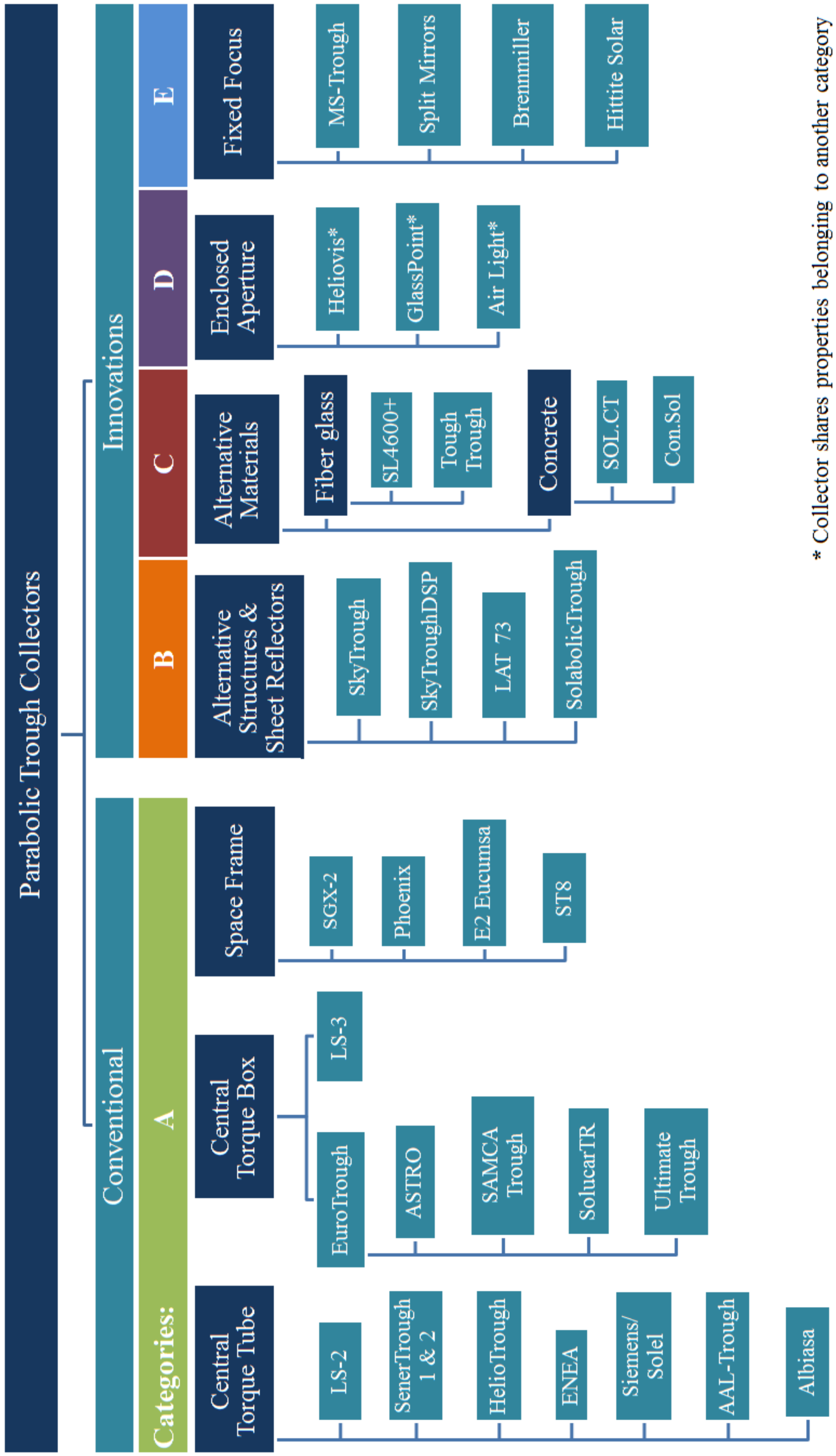


Figure B-1 Genealogy of parabolic trough collectors

II. Category A: Conventional Collectors

A1. LS-1, LS-2, LS-3

a) 

b) 

c) 

Figure B-2 a) LS-1 **b)** LS-2 **c)** LS-3 collectors at SEGS [1]

The LS-1, LS-2 and LS-3 collectors developed by LUZ Industries, demonstrated the implantation of parabolic trough technology for large-scale energy production in modern times. Between the 70´s and 80´s there were attempts to introduce the technology to operate at temperatures up to 260°C, which proposed a use for industrial process heat. Due to the degree of complexity and challenges to conceive a new technology at industrial scale, there was not much response. The main reasons were the high initial cost, the long term return of investment and the cheap fossil energy.

The Mojave Desert, California, USA is a region with Direct Normal Irradiance (DNI) value of about ~8 kWh/m^2 per day (2888 kWh/m^2 per year)[1]. There the nine Solar Electric Generating System solar power plants were established up to date in three different nearby locations: Daggett (SEGS I-II), Harper Lake (IIX-IX) and Kramer Junction (SEGS III-VII). Each of them was designed as a hybrid plant with a backup firing from natural gas, yet with solar energy as

[1] World Bank Group, www.globalsolaratlas.info

primary source [2]. The first solar fields SEGS I -II used the models LS-1 and LS-2, both with a central steel torque tube and cantilever arms to support the glass mirror facets. The 4 mm thick silvered glass mirrors were manufactured by Flabeg GmbH with low iron content characterized with a solar weighted transmittance of 98%, whose back part of the facets was coated with a sequence of protective layers. Their rigidity, corrosion resistance and durability of the geometrical and optical properties led to its application for the later model LS-3 and introduced in general a standard for mirrors into the CSP market.

The LS-2 and LS-3 were developed in order to increase the concentration factor and aperture area. An LS-3 solar collector assembly was composed of 8 modules, each of 12 m length. The structure of the LS-3 represented a better resistance against bending and torsion according to LUZ.

A2. EuroTrough

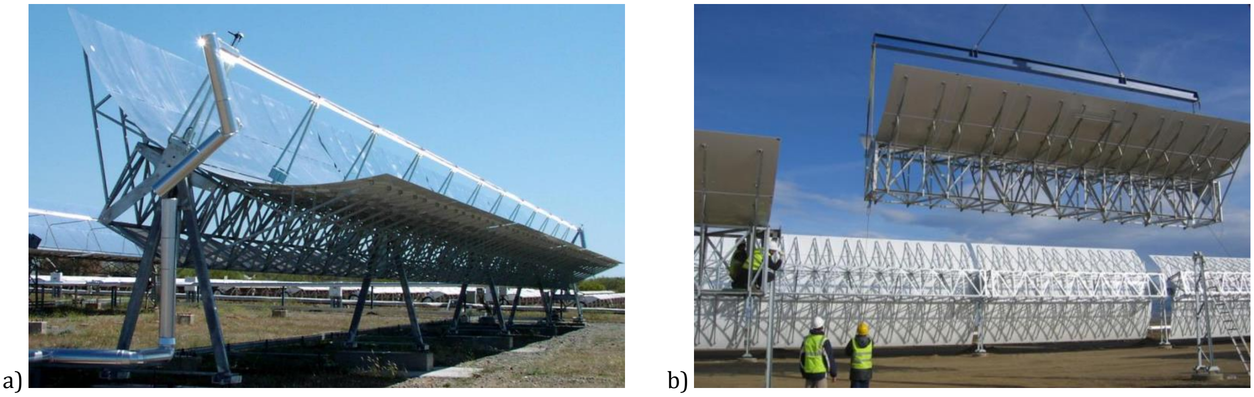


Figure B-3 a) EuroTrough prototype at the Plataforma Solar de Almería (source: Plataforma Solar de Almeria) **b)** SKAL-ET installation at the Andasol 1 Solar Power Plant (source: Solar Millennium AG)

The EuroTrough collector was developed in the year 2000 by a consortium of several industrial companies as well as solar research institutions[2]. The main motivation was to develop a competent collector for the market after the success stated at SEGS that could guarantee an outstanding performance at low cost. The EuroTrough project was funded by the European Commission for the development and qualification to promote electricity in the internal renewable energy market within the framework of the´Non-Nuclear Energy Program´ (1998-2001) [2].

The central torque box structure can be seen in Figure B-3. It is comprised of a pre-galvanized steel profile frame of about 1.4 m x 1.5 m over the collector´s length. On this structure 28 profiled arms (14 on each side) of the same material are mounted to support the 4 times 7 mirror facet lines. The structure is reinforced with endplates on each extreme, which rest on the bearing pylons and contribute to the torque transmission over the adjacent modules. At the same time the receiver supports are assembled to the upper part of the torque box, where ~4 m long receivers are mounted on-site. It is important to point out that the EuroTrough was developed on the basis of the well-known collector LS-3.

Essentially the LS-3 was state of the art on collectors by the time as well as the receivers and mirror facets. Therefore the dimensions for the EuroTrough were taken over from the LS-3:

[2] Inabensa (Abengoa), Pilkington, sbp, Fichtner, Flabeg, Iberdrola, Solel, Ciemat, Cres, DLR

module length= 12m, aperture width= 5.76 m, focus length= 1.71 m from the vertex of the parabola.

The receivers of type UVCA® (from Solel) were improved in regard to their optical and thermal properties, thus increasing the performance of the collector. At the same time Flabeg mirrors type RP3 were implemented, which correspond to the approved technology used in the LS-3. In terms of weight and material, the EuroTrough presented a 14% reduction compared to the V-truss design of the LS-3, with the possibility for further reductions in future derived designs [2]. The new central torque box structure enables the building of longer solar collector assemblies up to 150 m length (instead of 100 m), since the torque transmission and robustness significantly increased (see Figure B-4).

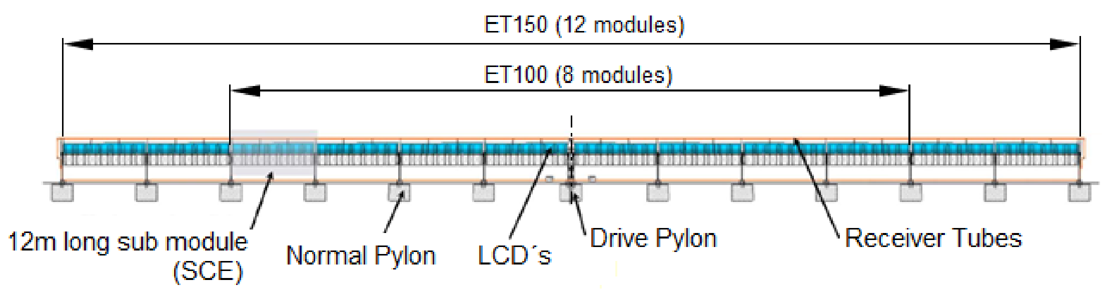


Figure B-4 EuroTrough solar assembly collector 100 m and 150 m length. Once commercialized by Solar Millennium the model was known as SKAL-ET [5]

Tests for optical analysis (photometry), thermal performance, stress of mirror fixing pads, flux measurements at focal region, tracking system and mechanics were performed.

The EuroTrough is known as the SKAL-ET at commercial scale. It pushed the technology into a new global era, starting with its implementation in the first (50 MW) solar power plants with thermal storage in Spain; Andasol 1, Andasol 2 and Andasol 3.

The growing market responded in a chain effect for alternative concepts of parabolic trough collectors similar to the EuroTrough design, to the LS-2 and other approaches such as space frame collectors.

A3. HelioTrough

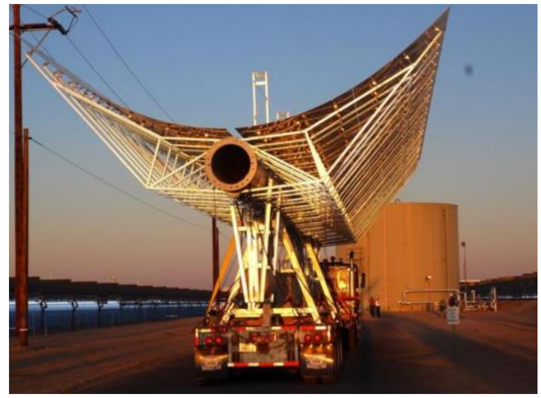
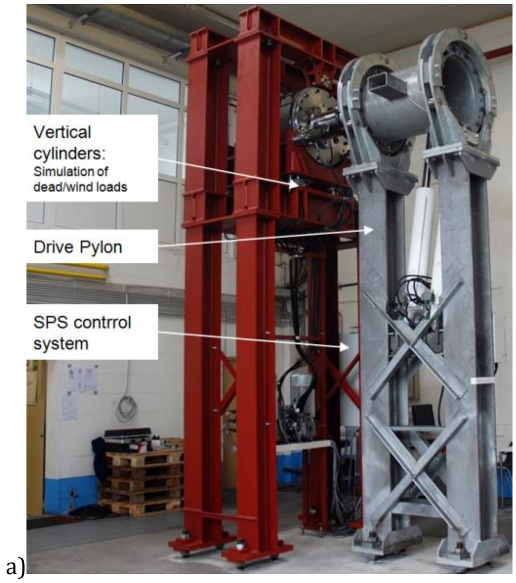
a)  b) 

Figure B-5 a) A HelioTrough collector module (length=19,1m, width=6,77m) during assembly on site between the drive pylon (bottom left) and the bearing pylon (bottom right) [6] **b)** HelioTrough module transportation from the assembly hall to the loop [6]

The HelioTrough of the European line of collectors was completed in 2006 and tested in a 400 m loop in 2009 at SEGS V, Kramer Junction. Its technical qualification character and production facilities are taken from the bench market of the SKAL-ET (´escalated EuroTrough´). Its design, however, shares similarities with the LS-2, which is also characterized by the central torque tube and the cantilever arms. The aperture width and module length increased with the HelioTrough development, to increment the effective aperture area and reduce the amount of components per square meter. The dimensions are 6.77 m of aperture width with 19.1 m module length, focal length at 1.71 m with a total of 191m per solar collector assembly and around 400 m per loop. The 48 parabolic mirrors concentrate the light in one module in a 90 mm diameter receiver, thus the cross section allows a 60% higher mass flow at same flow velocity, with related higher heat gain at constant pressure drop [7].

Regarding the optical and thermal efficiency, optimization is achieved thanks to the continuous aperture of reflectors, where the gaps at pylons´ level are eliminated. The continuous aperture reduces the implementation of components such as swivel joints between the SCE, simplifying both assembly work on site and manpower. Its structure and the implementation of RP4 type reflectors (thick glass and silvered reflective layer) with an accurate parabolic shape increase the optical efficiency, as well as its patented 3D joints that allow the precise adjustment of the reflectors. In addition, a new concept of drive and bearing pylons has been developed. It facilitates an uninterrupted transmission of the torque through the entire solar collector assembly (see Figure B-6). Also the collector's centre of gravity has been designed at the height of the torque tubes rotational axis with the assistance of the visible counter weights at the back part of the collector, thus reducing stress at the bearings and drive units.



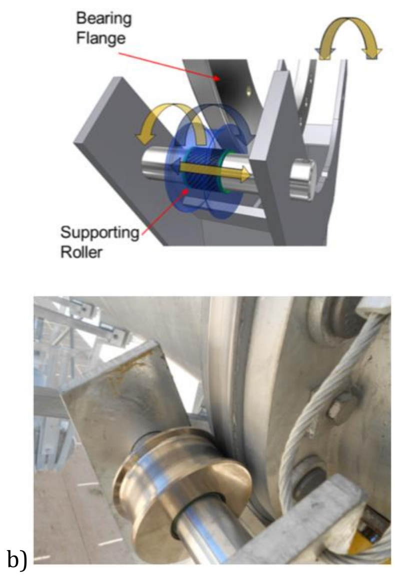


Figure B-6 a) Drive pylon at test facility in Cologne, Germany **b)** supporting roller at middle pylon [8]

A4. Ultimate Trough

Figure B-7 Installed Ultimate Trough [9]

The new generation of collectors in Europe and the world was developed between 2010 and 2012. A UltimateTrough module is characterized by its evident large aperture and length (7.51 m x 24 m). It saves up to 23% of the solar field cost in comparison to the EuroTrough [10]. Further advantages apart from the cost savings are the increased optical performance and the reduction of assembly parts [6].

The torque box is oversized up to about 1.85m x 1.85 m from which 24 arms extend to each side. These cantilever arms support the mirrors in 4 rows per 12 mirror of about 2m x 2m per facet. A gap between the outer and inner mirror rows alleviates frontal and lateral wind loads, reducing them up to 30% [10]. It is important to note that its large size and rigid structure are dimensioned to prevent deformations that could degrade the optical efficiency of the collector. Therefore further diagonal profiles were added to achieve sufficient stiffness of the cross-section. Since the centre of gravity and the rotation axis are located under the vertex of the parabola, a continuous mirror aperture through the solar collector assembly is achieved by eliminating the gaps at pylons level. At structural level, by means, at the joining between the steel structure and the mirrors a tension free junction is carried out to allow high variance and reduce the hazard of glass breakage [10].

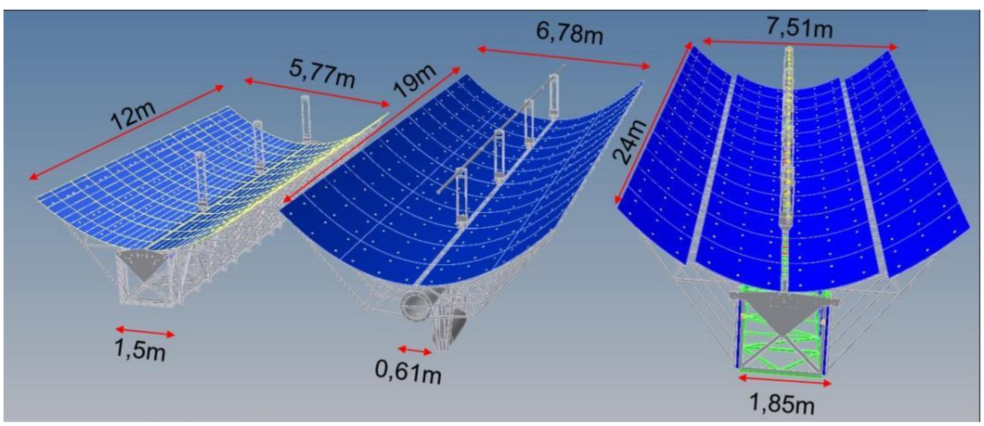


Figure B-8 Design and dimensions of the European development line of parabolic trough collectors: EuroTrough, HelioTrough, UltimateTrough [6]

Glass and steel are the main materials used in this collector. The selected steel for the hollow profiles was chosen to enable a worldwide accessibility with the common type S235 [11]. Regarding the assembly technology the “clinching method”[3] was firstly applied to build the torque box structure, reducing more than 50% of bolts and nuts in the solar field and offering a possible high automation degree, where assembly jigs remain necessary.

[3] Its origins are found in the automotive industry assembly lines.

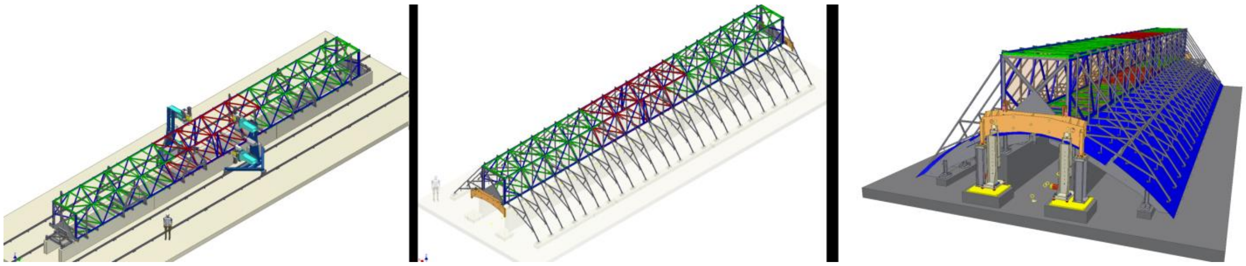


Figure B-8 Overview steps of a jig assembly line from the torque box frames until the fixation of the mirror facet on their support structure [6]

A loop was tested in 2012 at Harper Lake, California, leading to its commercial introduction. A first project is the operation in the DUBA Green Integrated Solar Combined Cycle Power Plant in Saudi Arabia since 2017 to provide 40 MW_{el}, where the combined cycle offers a total of 565 MW.

A5. Siemens/Solel

a) 

b) 

Figure B-9 a) 50 MW Solar power plant Lebrija 1 in the building phase [press picture by Siemens, April 13th, 2010] **b)** Installed trough loops at the still operating [credits: José I. Quintana, 2016]

The collector design of Siemens has been taken over from Solel and is based on the LS-3 concept, but uses a torque tube instead of the v-truss of the LS-3. In 2009, Siemens provided the collectors for the Lebrija solar power plant (50 MW) in southern Spain, which remains currently in operation [12].

A6. SGX1 & SGX2

Already in the early 2000's the company Duke Solar Energy developed space frames structures composed of extruded aluminium profiles with the DS1 collector.

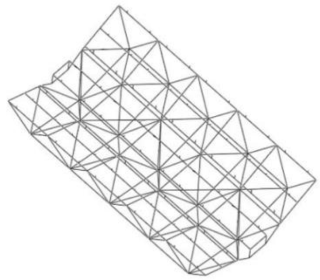


Figure B-10 Duke Solar space frame in the early 2000 s [3]

The collector line developed by Solargenix Energy (formerly Duke Solar Energy) with the National Renewable Energy Laboratory (NREL) proposes a new innovative concept within the conventional collectors' category, whose target is a more lightweight and standardized concept with agile assembly process, production and transportation logistics. The evolution of this concept led to the optimized SGX-1, implemented in the 1MW solar plant Saguaro, Arizona, and SGX-2, implemented in the 64 MW Nevada Solar One plant.

a) b)

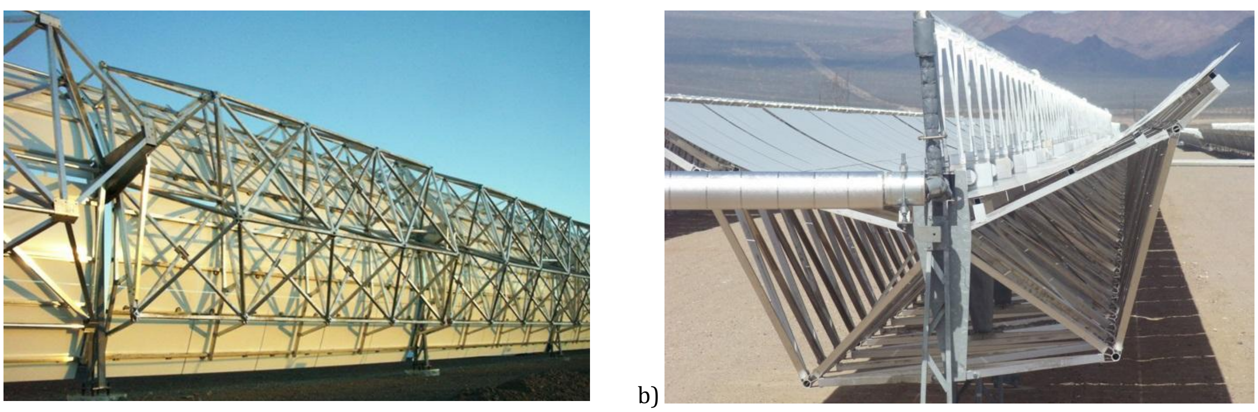


Figure B-11 a) and **b)** SGX-2 extruded aluminium profile space frame collector at 64MW Nevada Solar One solar power plant [13]

With the space frame concept it is possible to achieve SCAs from 100 m to 150 m in length per drive, for which fewer fasteners and welding works are required. The use of special profiles and knots offers an improved alignment of the reflective mirrors on an aperture area per module of 5.77 m per 12 m.

A7. SENERTrough (SNT-1) & SENERTrough-2 (SNT-2)

SNT-1 & SNT-2 have been developed by the Spanish company SENER as an inclusive product of its services as EPC (Engineering-Procurement-Construction) in projects worldwide. In fact this company constitutes a part of the consortium that raised the Solar Complex NOORo I, II, III in Morocco. There the solar fields 160 MW_{el} NOORo I and the 200MW_{el} NOORo II implement their parabolic trough collectors SNT-1 and 2, respectively.

Both collectors use a torque tube along the module, where the SNT-2 represents a +25% dimensioned scale version of the SNT-1. The main feature of these collectors are the cantilever arms, manufactured with thin sheet stamped technology that provides the parabolic shape and the support points for the mirrors. This mainly addresses the lightweight and the manufacturing method, while providing high precision and repeatability. This subsequently favours the geometrical accuracy and cost reduction.

a) 

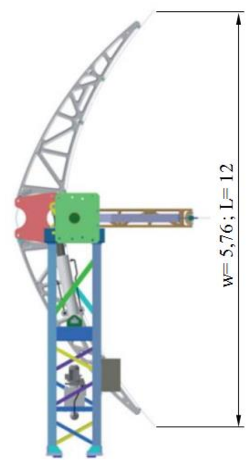
b) 

Figure B-12 a) SENERTrough stamped cantilever arms connected to the central torque tube and supporting mirrors. The collector contains a total of 28 single sheet arms and single mirror facets. **b)** Collector aperture and module length in meters. Note the structure pattern of the stamped arms [1]

The elements such as the torque tube, the arms and the heat element collectors' supports are made of carbon steel, due to its good strength ratio value [14]. Similar designs can be appreciated in the LS-2 and the ENEA collector.

a) 

b) 

Figure B-13 a) SENERTrough 2 collector module follows the previous concept. In total 28 longer stamped arms and single mirror facets are contained [15] **b)** Collector aperture and module length in meters. Note the structure pattern of the stamped arms [1]

A8. ENEA Collector

a)

b) 

Figure B-14 a) and **b)** ENEA´s parabolic trough [16]

The ENEA[4] collector is the first one to demonstrate the implementation of molten salt as heat transfer fluid in the solar field. The operational 5 MW solar power plant is allocated at the ENEL Archimede Power Plant in Sicily. The collector with specially developed receivers, such as the HCEMS-11, can operate with the fluid salt mixture of potassium- and sodium nitrate (40% KNO_3 60% $NaNO_3$) from 270°C up to 550°C at a design pressure of 8.5 bar [17].

[4] ENEA-*italian*. for Ente per le Nuove tecnologie l´Energia e l´Ambiente

The design of the trough possesses a central torque tube with cantilever arms made of metal sheets. The latter are cut in the form of the parabola and have additional stamped circular patterns, providing rigidity and lightweight to the structure. The dimensions per module are characterized by an aperture width of 5.76 m, a length of 12.5 m and a solar collector assembly of 100 m [1]. Moreover it establishes thin glass mirrors on special aluminium honeycomb facets, which provide a sufficient stiffness to produce very large panels, thus simplifying the assembly process [18].

A9. AAL-Trough (Gen.4.0)

a) 

b) 

Figure B-15 Alternative torque tube structure of the AAL-Trough composed of two shells shaping the hexagonal unit. Photography a) and b) correspond to a CSP collector field under construction without receivers or connecting pipes. The claimed´wing´ design of the cantilever arms is shown mounted on the torque tube [19]

The collector developed by the Danish company Aalborg CSP presents an alternative central torque tube unit and cantilever arms. On the one hand the torque tube is featured with a hexagonal shape, composed of two bent metal sheet sections along the module. On the other hand there are the cantilever arms, claimed as 'wing design', which bring support together with longitudinal steel profiles for the glass mirrors. The collector is dimensioned like the classic SKAL-ET150 with an aperture width of 5.77 m and 12 m for a maximum SCA of 150 m.

A10. ASRT0


Figure B-16 ASTR0 collector by the company Abengoa Solar, 2007 [20]

The ASTR0 collector is very similar to the EuroTrough. It has a torque box design, yet with redesigned low cost steel profiles and implementation fasteners instead of welds to build the structure. One of the very few changes is the reduction of the number of cantilever arms and the use of longitudinal purlins to support the reflector panels. This collector has been introduced in Spain (e.g. Solnova) and projects in the north of Africa. The performance is claimed to be similar to the EuroTrough, with a slightly cost reduction [20].

A11. Phoenix (3.2)

a) 
b) 

Figure B-17 a) Final Structural space frame of the 3rd generation b) Phoenix Gen 2.0 forerunner of the Phoenix 3.2 which did not meet all requirements. The space frame structure can be appreciated [20]

The Phoenix collector follows Abengoa Solar series line of development. Requirements for this generation were set to achieve an economical concept in terms of manufacturing, materials and process of assembly, while maintaining an accepted optical performance. Consequently torsion stiffness, alignment and resistance to wind loads are targets in the concept.

The space frame structure is made out of 80% aluminium with steel torque arms enabling a 60% higher torsion stiffness than that of the ASTRO collector. Furthermore the assembly time is reduced to around one fifth. The optical performance was approved within the generation 3.2 and attains ~ 10% cost reductions compared to the ASTRO collector [20].

A12. E2 (Eucumsa)

In 2011 Abengoa steps forward with their next generation of collectors. The E2 or Eucumsa is a variation of the Phoenix design composed of a steel space frame structure. It requires a jig alignment of the mirrors and contains improved purlins for their mounting on the steel structure. The mirrors used are glass reflector panels and their overall production saves around 10% of cost against the ASTR0 collector [20].

a) b)

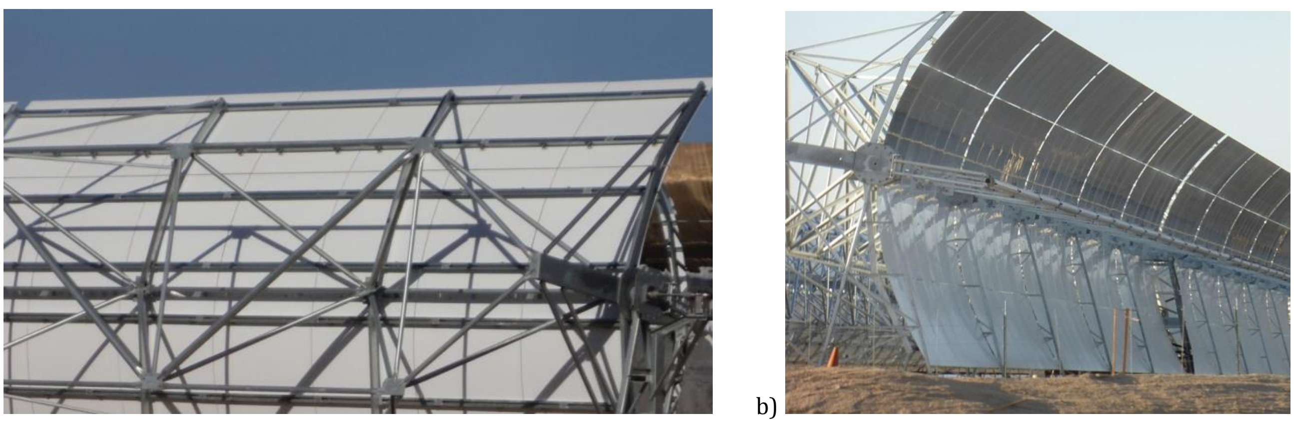
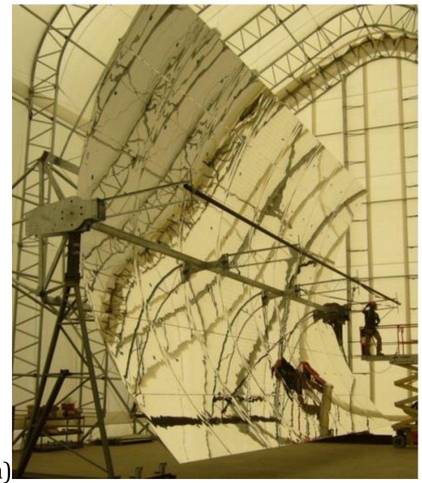


Figure B-18 a) E2 collector back view of the space frame [1] **b)** front view [21]

One reference project is the 280MW Solana Generating Station[5] in Arizona implementing these collectors. Another one is the 100 MW KaXu Solar One in South Africa.

[5] Web-Link: https://solarpaces.nrel.gov/solana-generating-station

A13. SpaceTube (ST8.2)


a)

b)

Figure B-19 a) ST8 Space Tube with glass mirrors and **b)** with composite panels [20]

The SpaceTube8.2 (ST8.2) built by Abengoa Solar in 2013 is the largest solar collector worldwide of the conventional collector category. Under the ´Sunshot Initiative´ of the US Department of Energy the company strives not only to develop this large aperture collector, but also to improve different production and assembly elements of their predecessor designs.

Further manufacturing optimization of the collectors´ sub-structures, lower input material costs & mechanized production are the target for its development. The project named ´SolarMat´ reports an estimated for the solar field costs at 91.83 $\$/m^2$ [22].

The SpaceTube's frame eliminates welded assemblies and large jig alignments, thus reducing specialized manpower. Its manufacturing and fabrication apply stamping techniques and the assembly comprehends an automated process that achieves an accurate mounting of the parts.

The latest version of this collector is the ST8.2. For this line innovative approaches in its structure were also tested, for example the use of composite panels as reflecting components and also adaptations for the use of molten salt as HTF. The implementation of this model is to be applied in the *Mohammed bin Rashid Al Maktoum Solar Park*, in Abu Dhabi. It is a 950 MW hybrid project, where 700MW will be based on CSP and 250 MW on PV.

III. Category B: Metal structures & sheet reflectors

B1. SkyTrough & SkyTroughDSP

a) 

b) 

Figure B-20 a) SkyTrough Parabolic Solar Concentrator in Arvada (source: http://evworld.com/) **b)** SkyTroughDSP [23]

The US-American company SkyFuel developed a line of parabolic trough collectors targeting a significant cost reduction trough simplified lightweight structures and the utilization of reflective polymer films.

As pioneers in this area they developed a reflective adhesive material to substitute the commonly used glass mirror panels. This polymer reflective layer is offered under the name ReflecTech and its nominal thickness is 0.1 mm. The SkyFuel Company claims to have developed a 100 $/m^2 collector, namely the SkyTroughDSP shown in Figure B-20b [24]**.**

In 2010, the first collector was the SkyTrough with an aperture width of 6 m, module length of 13.9 m and a solar collector assembly of 115m[6] (see Figure B-20a). SkyTrough attained a 36% cost reduction in comparison to a EuroTrough 150 collector [25]. Regarding the optical efficiency, 75% is given in the data sheet and for the thermal efficiency at operating temperatures with 72% [25].

The SkyTroughDSP (Dispatchable Solar Power), follows the same previous design, yet with 30% scaled up aperture dimensions and with the suitability to operate with molten salts as heat transfer fluid. This collector has an aperture of 7 m, a module length of 17.74 m and a solar collector assembly of 148 m. Its optical efficiency was established to be at 76% ±4.8% with a

[6] The given length includes the modules, pipe-, control- and drives connections

95% confidence [27] and 75% in the datasheet, where a DNI of 1,000 W/m^2 is assumed. With that, the thermal efficiency for an oil based system operating at an inlet temperature of 300°C and an outlet of 400°C was estimated at 72.5% ±5.66% (95% confidence) [27]. In the following case the estimated thermal efficiency for a molten salt operating system at 300°C at the inlet and 500°C at the outlet was at 70.5% ±5.84% (95% confidence) [27].

a) 

Figure B-21 Reflectors been installed in a SkyTroughDSP collector [28]

Both collectors utilize a space frame based structure with standardized aluminium tubes (Al 6051) [29] and exploit the lightness of the design to alleviate the requirements on the holding structure and drive mechanism. Because of standard elements neither further jig assembly nor an assembly hall is needed. The aforementioned reflective foil is glued onto aluminium sheet rolls, which for the mounting slide into precision ribs, thus giving the parabolic frame shape as shown in FigureB-21.

The characterization of these collectors is rich in information and has been implemented in small scale applications or demonstration loops. Currently the company SkyFuel is developing the *Chabei 64 MW Molten Salt Parabolic Trough Power Station* in the South East China.

B2. Large Aperture Trough (LAT 73)

a) b)

Figure B-22 a) Large Aperture Trough by Gossamer Space frames and 3M at a pilot loop in SEGS I **b)** Reflector panel mounting (top) and detail of panel to panel connection (bottom) (credits: 3M, Sunshot Initiative)

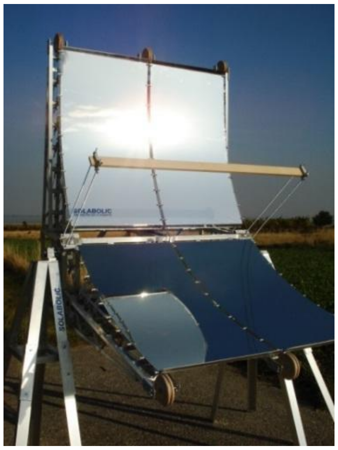
The LAT 73 is a development of 3M and Gossamer Space Frames[7]. As with the SkyFuel collectors, an aluminium space frame and a type reflective polymer film is used, in this case the Solar Mirror Film 1100 produced by 3M.

The collector is dimensioned with an aperture width of 7.3 m and a module length of 12 m for a total solar collector assembly of 192 m, which corresponds to 16 modules per SCA. Its operation with a receiver of 70 mm diameter enables a geometrical concentration ratio of 103 [30]. Furthermore an intercept factor of 98% is claimed at a slope error of less than 1.5 mrad, including the mirror´s and space frame´s slope errors [31]. The utilization of these space frames enables high optical alignment accuracy. The optical reflectivity of the foil is maintained at 95% ±2% (solar weighted total hemispherical reflectance) after proven 14 years [30].

Dan Chen, Business Manager of 3M, claims in an interview a 25% solar field cost reduction with the LAT 73 in comparison with conventional concepts [32]. It uses over 40% fewer components, which result in around 20% material cost savings, adding to that the absence of assembly-jigs and more simple assembly steps [30]. For example, the installation of one of 20 reflectors is alone stated at 3 man-minutes per facet (see Figure 22-Bb). Furthermore 20% less receivers and pylons are needed as a consequence of the larger aperture.

[7] Former technology developed by Gossamer Space Frames: see A6 SGX1 & SGX2

B3. Solabolic Trough

a) 

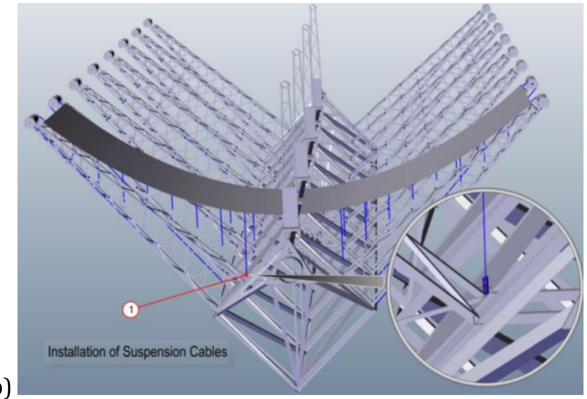
b) 

Figure B-23 a) Physical model [33] **b)** Torque box and truss arm structure with emphasis on the installation of the springs and suspenders [33]

The SolabolicTrough is inspired by the principle of suspended (or hanging) bridges, where parabolic shapes are also used. The structure itself implements a torque box and profiled truss arms with roll-ups at each end for the mounting of the aluminium coated sheet reflectors[8]. For the physical model in Figure B-23a, conventional dimensions were applied: aperture 5.77 m and focal length 1.7 m. The strived solar collector assembly shall total 150 m and with single 12 m long modules.

The concept aims to tense the reflectors in the ideal parabolic shape by cables and own patented mounting springs. Two main challenges were encountered, stated by the developer after the prototype phase.

1. An ideal optical alignment was not achieved after tensing the cables in their position, due to the expansion of the cables and the sliding of the connecting points [34].
2. The requirements on the springs were constraining the proper tensile distribution on the truss. A special manufacturing of these springs was needed in order to fulfil their corresponding function, yet for the intention of the concept, this would mean an increase in complexity and costs [34].

[8] Thin glass reflectors were considered as an option as well.

The concept itself suggested a 20% weight reduction per unit aperture area and a 35% reduction of a solar field costs in comparison to a conventional solar collectors' field. A parabolic trough of 10 m aperture was assumed for the cost estimation, yet the practical implantation was still constrained to the two facts mentioned above [34]. However, thermal and optical data are rather based on simulations, and it is worth mentioning that the design had to be adapted in order to overcome the challenges.

The approach suggests a different tracking mode, a so called vertical azimuth tracking system and the use of chains instead of cables to overcome the described challenges. In Figure B-24 additional photovoltaic devices shall support the tracking system. The new concept suggests the implementation of the collector for small scale applications, reason for which the concept will not be further evaluated.

Figure B-24 "Tracking photovoltaic modules with the same tracking system of the parabolic trough collector"[source: Solabolic GmbH]

IV. Category C: Non-metallic materials

C1. Solarlite 4600+

a) b)

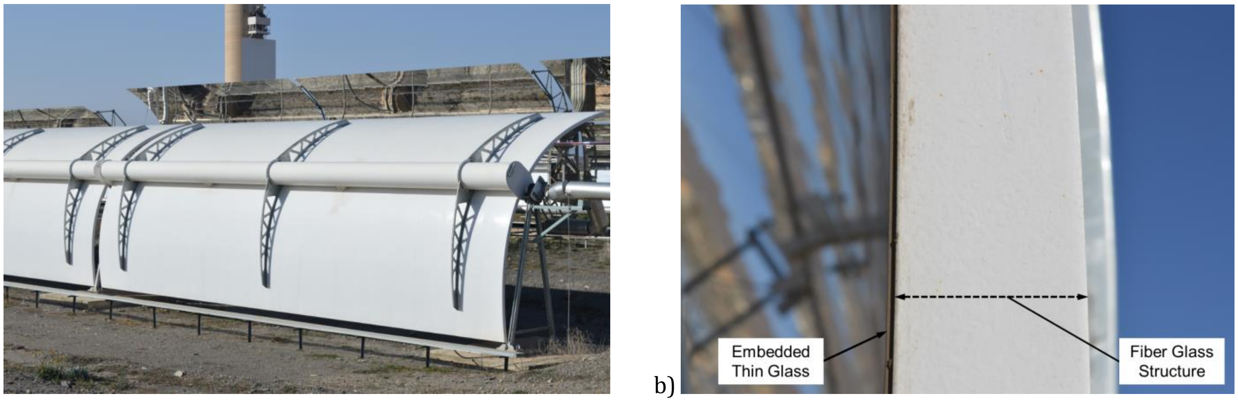


Figure B-25 a) Solarlite SL 4600+ at the DISS facility to demonstrate the Direct Steam Generation (DSG) process, Plataforma Solar de Almería **b)** Parabolic shape integrating fibreglass and foam in the core, photos taken in 2019

The German company Solarlite developed collectors that implement sandwich composites of fibreglass and resin, which enclose hard foam at the core of its central body. The latest generation, the SL4600+, uses a torque tube to assume the torsion forces and has additionally three pairs of steel stamped sheet arms to support the parabolic structure. This collector has been deployed for Direct Steam Generation and operates the first 5 MW_{el} power plant of its kind in Kanchanaburi, Thailand.

The aperture width is 4.60 m with a module length of 12 m. The SL4600+ operates with a receiver of 70 mm in diameter, thus attaining a concentration factor of 66:1. The flexible thin glass facets are glued on the parabolic fibre reinforced glass structure as shown in Figure B-25b. The combination of the light weight composite and partial steel structure amounts a specific weight of 19 kg/m^2 [35].

According to the manufacturer the optical efficiency is 75%, while the DISS test facilities measured 77%. Solarlite informed that a new generation is in perspective with a larger aperture (5.77 m) and a steel/glass design including composite panels and enhanced optical performance.

C2. ThoughTrough

a) 

b) 

Figure B-26 a) Prototype parabolic trough using toughTrough mirror technology **b)** Backside of the prototype module. Foto: toughTrough GmbH, Lübtheen in Mecklenburg-Vorpommern,. 2011 May

ToughTrough GmbH developed innovative solar reflector panels using composite sandwich materials, steel and thin glass. Beyond this, the highly automated and precise manufacturing process derived from the aeronautical and automotive sectors, aim at a better performance, lightweight and higher stiffness. Its design for industrial scale manufacturing achieves a 25% cost reduction in comparison to existing models [36]. The main reduced costs drivers include -25% in foundations and more than -25% in the mirror shell, collector frame and pylons together, according to CEO Carsten Holze [36].

The prototype consists of a torque tube and four continuous longitudinal segments of their parabolic facets. They are mounted on further steel arms which extend from the central body. Those facets can be customized from a length of 1.7 m to 18 m and a width of 1.6 m. The structure is based on a front layer of thin glass, followed by a core of polyurethane (foam of roughly 25-50mm thickness), which is enclosed within a steel/fibreglass composite back layer. [37]

In comparison to the EuroTrough design 50% of mass reduction is achieved and around 1 ton less of weight per module [36]. Further tests have shown a reflection of 95.5% with accuracy of 1 milliard and under wind loads[9], below 2 millirad. Earthquake tests proved a safety up to a magnitude 8 on the Richter scale. The company's scope covers not only parabolic trough technologies, but also heliostats and solar dishes for other CSP approaches.

[9] At 60° degrees and 120° degrees

C3. Sol.CT

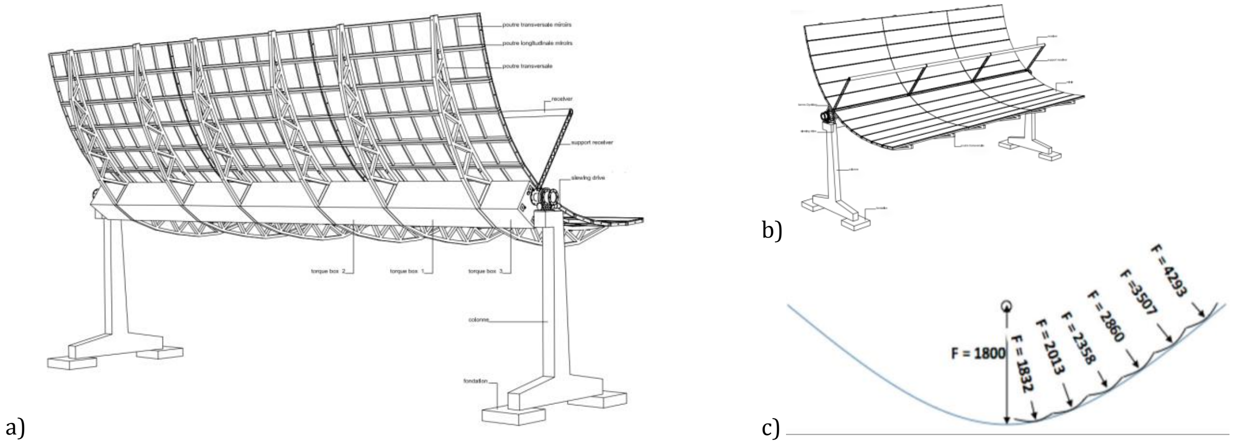


Figure B-27 a) Concrete structure with segmented torque box, pylons, transversal beams and parabolic frame **b)** design front view with longitudinal cold bent mirrors **c)** Focal scheme of single integrated mirror plates approximating the ideal parabola (source: Alto.Solutions) [38]

Alto.Solutions presents a collector concept composed of ultra-high performance concrete (UHPC) precast elements. Its configuration is analogue to a conventional collector, which uses a torque box and transversal supporting structures for the mirrors. The latter correspond to another special feature of their concept, since it uses mechanically cold bent mirror plates instead of glass facets.

Figure B-27c shows the schematic cross section of a final installed contour of the adjacent mirrors. The flat plate glass has a thickness of 2 to 3 mm and uses a silver reflective layer with 94% reflectivity. Finally facets of 1 m per 1 m are integrated in the latest of their designs to reduce the optical error.

A pilot plant with 1500 m^2 aperture is planned for the year 2019 according to the manufacturer. Collectors with the dimensions of 6 m[10] width per 12 m length are intended and the focal length is increased up to 2 m to 2.2 m, to enhance the intercept factor. Regarding the optical and thermal efficiency data is limited, since a prototype has not been completed yet. Furthermore a slewing drive unit is integrated for the tracking mechanism.

Alto.Solutions estimate the collector costs at 69 €/m^2 and a reduction of 40% for a solar field cost based on SAMs database [39].

[10] The manufacturer states possible 2 m and 9 m aperture width collectors

C4. ConSol

a) 

b) 

Figure B-28 a) Demonstration of a two modules prototype operated with a central gear motor **b)** Laminated concrete surface segment with a flexible silvered aluminium reflector [40]

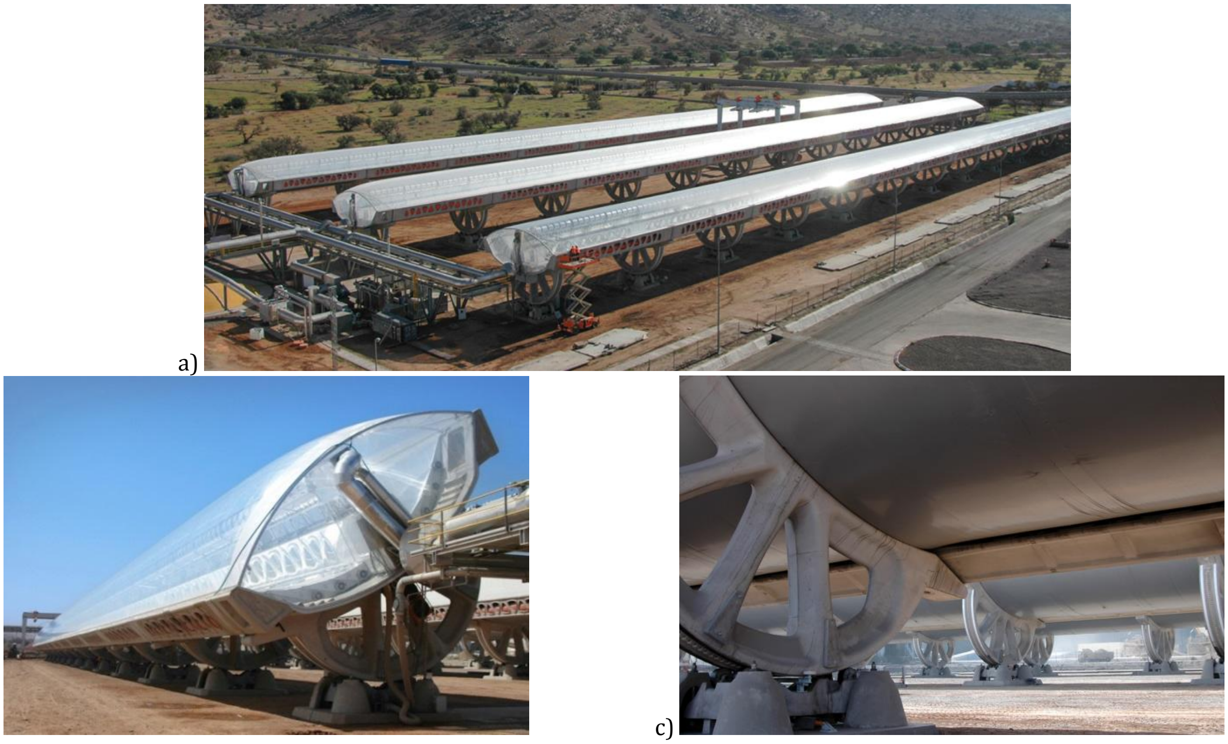
The ConSol (Concrete Solar Collector) project represents a different approach using alternative high performance concrete material. The demonstration prototype is composed of on-site casted elements partly of Nanodur® and partly of normal strong concrete C35/45. The collector contains two parabolic modules and their respective geared support structures. It is dimensioned with an aperture of 5.77 m per 12 m length and a shell thickness between 3.5 cm and 5.5 cm (see Figure B-28).

The reflectors are silvered coated aluminium sheets, which are adhered to the concrete shell with a double sided adhesive tape. The reflectance of the mirrors was measured at 92.3%. The intercept factor in zenith position of only 46% could be adjusted up to 86% by repositioning the 70 mm in diameter receivers [40]. The expected value for the light´s deviation is a consequence of the uncertainty of the material´s widening in the casting process. In regard to the drive mechanism, a central unit for a row of adjacent collectors was taken away, since simulations showed insufficient resistance towards torque loads induced by wind.

In terms of efficiency an optical peak is characterized with 67%. A power output of 240.484 kW lead to a thermal performance of 58% at 800 W/m^2 irradiation [40]. Investment costs of a ConSol solar field (compared with Andasol) are estimated at 261 €/m^2. Projected improvements in the design aim material cost reductions from 76 €/m^2 to 38 €/m^2 [40].

V. Category D: Enclosed Aperture Collectors

D1. Airlight



a) b) c)

Figure B-28 a) Deployed Airlight collector loops in the pilot plant Ait Baha, Morocco, 2014 **b)** Wide and enclosed aperture of the collector with its body structure made of precast concrete elements **c)** Transverse girder element and PVC/PES (coated polyester fabrics) membrane [41]

The Swiss company Airlight developed a large aperture area collector based on fibre reinforced concrete and an inflated polymer membrane as structural material. The latter includes a reflective polymer film, which is glued a parabolic shape. The aperture width of the structure is 9.7 m and the length of one module solar collector assembly is 210 m long [1]. Its application was developed for industrial process heat production as well as for electricity generation.

A pilot power plant was built near a concrete factory in Ait Baha[11], Morocco, from 2012 to 2014, for which an alternative storage unit was constructed based on a special container filled with gravel [42]. The receiver of this collector is adapted for air as heat transfer fluid, which corresponds to a further special feature. The air flows through the collector in large sized pipelines and arrive at the inlet with 250°C and 570°C at the outlet of the collector.

[11] Coordinates: 30°13'01.7"N 9°08'57.5"W [42]

The collector is to reach its maximum solar to thermal efficiency at 60% [41] to 64% with a thermal output of 1 MW_{th} per row. An assumption of a thermal-to-electric conversion efficiency of 35%, expects a negligible parasitic loss of 1.8% of the power output, consumed by the fans circulating the process air. [43]. A publication according to *Braid 2011* states the reduction of the performance of this collector, first due to transmission and reflection losses, second to inaccuracies of the reflective layer and third due to fluctuating inflation pressure of the membranes [44].

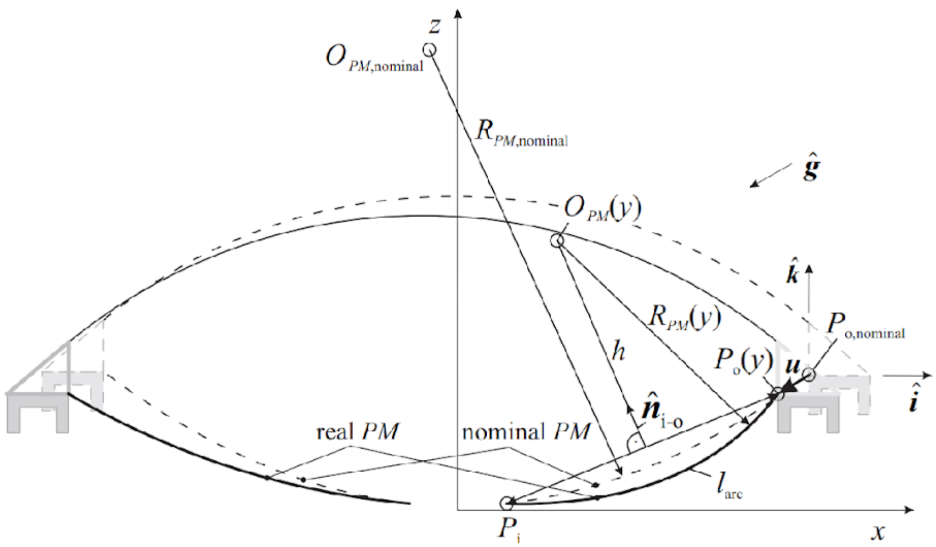


Figure B-29 Variation of the primary mirror PM due to the deformation caused by gravitational forces. The gravitational force direction is described by $\hat{g}$ and its effect by the dashed lines [44]

The ideal radiative flux at the receiver aperture is reduced by 8.5% due to transmission losses introduced by the concentrator top membrane, and by an additional 6.3% because of reflection losses on the mirrors [44].

Summing up, the collector is based on materials like concrete (Rapid Hardening High Performance), stainless steel, rocks, and for the membranes: BO-PET (biaxially oriented polyethylene terephthalate) as reflective layer, ETFE (ethylene tetrafluoroethylene) as translucent external film and PVC (polyvinyl chloride) as bottom layer.

D2. HelioTube

a) 

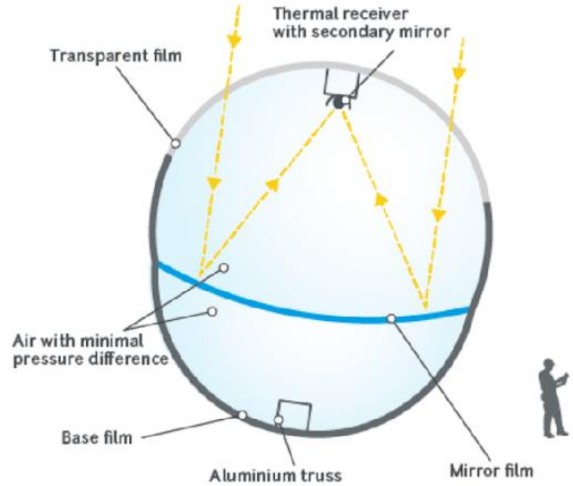
b) 

Figure B-30 a) HelioTube collector: finalist in the Energy Globe World Award 2017 [45] **b)** Scheme of the two segments inflated tube and main components [46]

The Austrian company Heliovis AG offers the HelioTube collector, which was developed in the framework of Horizon 2020 of the European Union. The concentrator, enclosed in an inflated plastic film, defines the reason for its inclusion in the Category D. A collector is dimensioned with 9 m in diameter and a length of 220 m and can be implemented in regions with high DNI values (above 1900 kWh/m^2) [46].

The materials used for the structure are based on steel and aluminium. The inflated tube is composed of a transparent ETFE layer, a reflective membrane of PET and a complementing base film of PVC. The mirror film separates two segments being inflated at different pressures, thus shaping the parabolic layer, which has its focal point at the upper extreme of the circle.

Figure B-30 shows a cross-sectional scheme of the concept, where also the implementation of an auxiliary mirror can be seen. It is claimed that temperatures up to 400°C can be reached, thus achieving a thermal capacity of 1 MW$_{th}$ for each tube.

A possible cost reduction of 55% [46] can be reached in comparison to conventional parabolic trough collector systems, due to the advantages in manufacturing, transporting, erection and maintenance procedures..

D3. GlassPoint

Figure B-31 a) Pilot plant configuration of suspended parabolic collectors and receivers in an advanced greenhouse structure **b)** Collector row configuration at the Miraah project with an additional V-truss structure on the back of the mirror panels [47]

In 2012 GlassPoint demonstrated the housed collectors in a large scale pilot plant for enhanced oil recovery (EOR) in the south of Oman; see Figure 70a). Its capacity delivered 7 MW_{th} steam energy, averaging 50 tons of output steam per day. Today they are completing a 1000 MW_{th} (1GW_{th} steam energy) solar field for this application named Miraah with an equivalent of 6.000 tons of output steam per day; see Figure 70b). Enlarging the solar field the natural gas consumption for steam production shall be lowered to 20%. The gas resources would be used only at night or when solar energy is not available.

The aperture field of GlassPoint is enclosed in an advanced agricultural greenhouse, where the collectors and the fixed receivers are suspended and driven by steel rods from the ceiling[12]. Inside the structure, collectors are protected from the present environment at sites with strong winds, sand and humidity.

The latest collector has an aperture of 7.64 m per 177 m row length inside the 6 m high glasshouse. The aluminium reflectors are embedded in a lightweight parabolic honeycomb structure, which enables a drive cable system to operate as tracking mechanism with 0.01 degrees of accuracy. Today a mirror panel weighs 1.2 kg/m^2, which corresponds to 18% mass reduction compared to the pilot design [48]. The mirror panels including the frame of the first collector weighted 4.2 kg/m^2 and were compared to the solar field dimensions of Andasol 1. In

[12] see Figure B-31a

this scenario a total material usage of 40 kg/m^2 vs. 134 kg/m^2 was estimated with reductions mainly in concrete and metals [49].

Further subsystems were improved in the new generation like drives, greenhouse structure material reduction, assembly records and optical performance, among others. Without these improvements a scaling of the pilot plant would represent a cost reduction for the solar field of 10% to 20%, where costs of subsystems could be reduced to 50% [48].

The global efficiency at zenith angle 0° and DNI 950 W/m^2 is given as result of a model between 66%-68%. 2% of losses are considered due to the soiling and possible roof structure shadowing, glazing losses and the use of an air-stable selective absorber coating and non-vacuumed receivers [49]. GlassPoint assures that these losses are compensated by the zero operational wind speeds and the soiling removal system. In regard to the efficiency of the new generation information was limited, but this new collector implements evacuated receivers and represent 99.9% intercept factor at the focal point.

An automated cleaning device was developed, which operates daily at least on half of a roof and once every night with full recaptured washing fluid. Due to dust deposition the operational performance of the pilot plant showed a drop of 12% of the efficiency during a sandstorm [49].

a)

b)

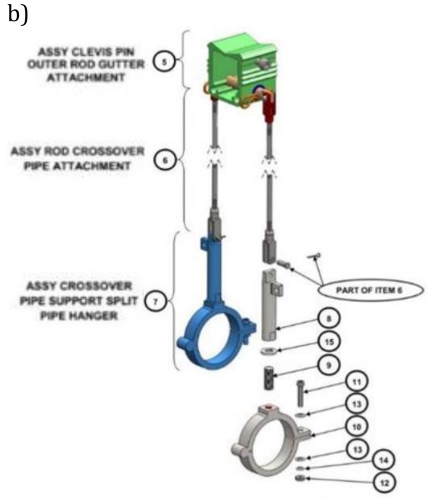


Figure B-32 a) Solar field after a sandstorm [47] **b)** Visual concept for the suspension mechanisms of the fixed receivers [49]

VI. Category E: Fixed Focus

E1. Hittite Solar

a) 

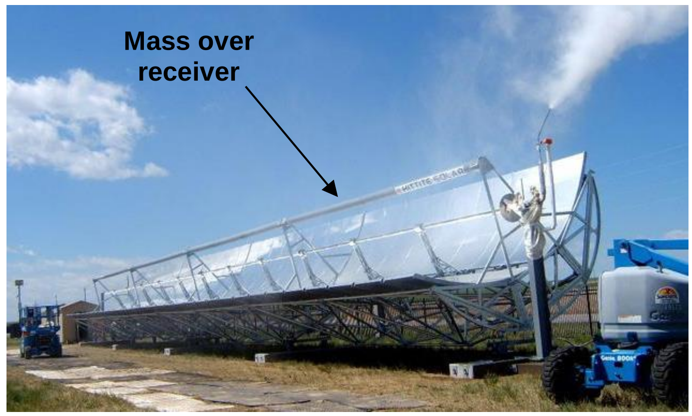
b) 

Figure B-33 a) Hittite Solar fixed focus collector with counterweight **b)** solar collector row [50]

The Turkish collector from Hittite Solar Energy was developed to operate for superheated direct steam generation (DSG) up to 500°C. The main motivation was to present a collector that could operate without constant breakdowns of the piping connectors. Their approach was to fix the receiver on the rotating tracking axis and to balance the collectors' centre of mass on it. This explains the counter weight above the receiver. A solar collector element has an aperture area of 6 m per 12 m, resulting in 48 m long a solar collector assembly.

The parabolic surface is embedded on a semi-circular structure with profiled and stamped metal sheet parts, as can be appreciated in Figure B-33a. The outer circumference serves as the support of the modules on guidance wheels at ground level. In regard to the torque unit a metal space frame between the semi-circular support units is responsible for its transmission, which also brings support to the modules´ reflectors.

The applied reflectors are based on thin glass of 1.5 mm thickness laminated on aluminium sheets, which means a gain of lightness, better optical performance and an economical advantage. The collectors have been tested four times with increasing output until 200kW$_{th}$. [50]

E2. Brenmiller

a) 

b) 

c) 

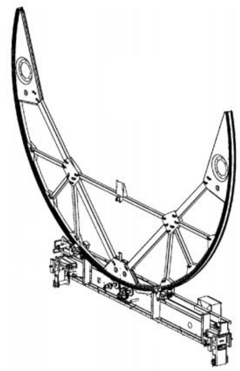
Figure B-34 a) Brenmiller trough module with a fixed focus receiver tube in 3D CAD [51] **b)** Prototype with continuous receiver along the solar collector assembly at the Negev Desert near Town Dimona, Israel [52] **c)** Collector with an alternative V-Truss structure as heat collector element support [53]

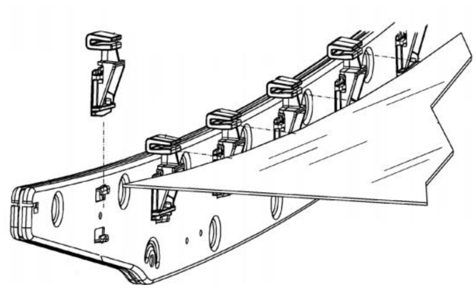
The Israeli parabolic trough of Brenmiller[13] Energy was developed as an extending feature to demonstrate their thermal energy storage technology, namely the bGen™. Its functionality adapts to various energy inputs like heat and electricity to provide industrial process steam [53].

The collector was developed mainly for direct steam generation (DSG) and uses fixed absorber tubes. The modules are directly connected to each other at the height of the circular frame, and no welding assemblies are necessary. This frame is composed of pre-galvanized parts with an outer circular edge and an inner parabolic edge that has its focus at the geometrical centre of the circular profile; see Figure B-34a. The centre of mass, however, is not located at this point. Each of these supporting structures is equipped with a motorized drive.

[13] CEO Avi Brenmiller was the former CEO of Solel (before LUZ Industries) as it was bought by Siemens AG

A pair of torque tubes, supporting the tempered glass reflectors, is mounted for torque transmission at each end of the circular frames [54]. These reflectors are mounted with engineered clips which propose an innovative method for mirror alignment; see Figure 74c.


a)


b)

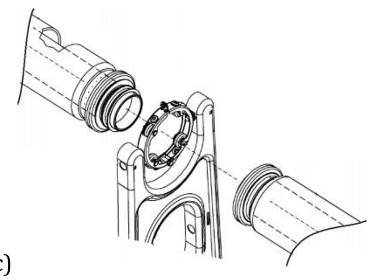

c)

Figure B-35 a) Circular frame mounted on the support and drive bases. Note the location for the torque tube units at the upper part of the framework **b)** clamping method concept for mirror support and alignment **c)** Illustration of the receiver tubes bearings at the HCE proposing a direct flange, where the outer circumference of the bearings is intended to move relative to the static absorbers [54]

In terms of assembly, it requires a jig assembly post for the torque tubes, the space frame and mirrors. To avoid the conventional procedure of land levelling an alternative procedure was engineered: the so-called´floating` solar field. The collectors are mounted on bases connected by rails, and this way the collector modules were rolled to their final position. Further technical data on this collector are rather limited in terms of dimensions, performance and costs, since the troughs´ line of development was discontinued and will remain in that stage, due to R&D priorities of Brenmiller´s main technology [55]. Nevertheless, a project of the company called Rotem 1 pretends to combine CSP with natural gas in order to demonstrate the 16 h storage with a plant of 1.7 MW.

E3. Split Mirrors

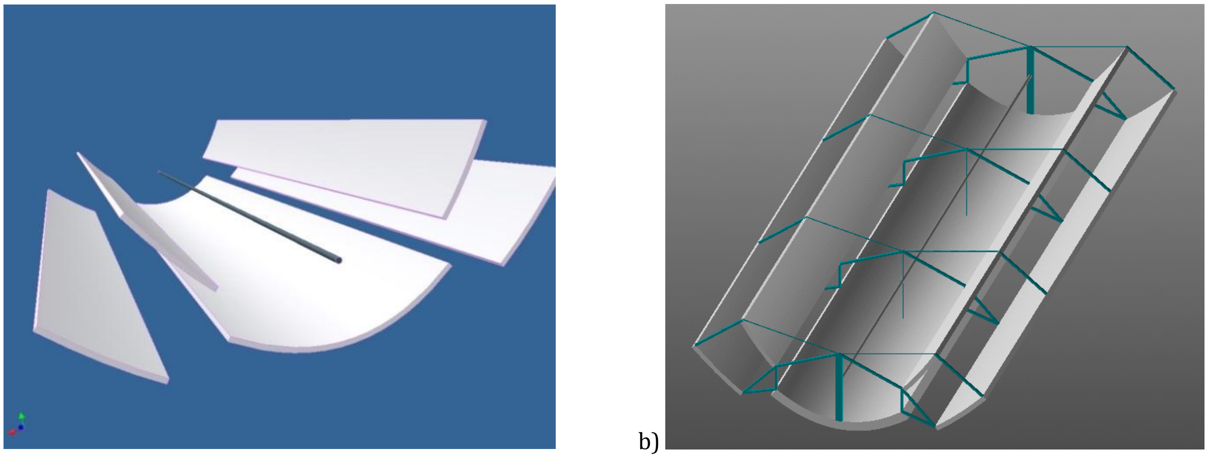
a) b)


Figure B-36 a) 3D concept exposition of the fixed focus collector with segmented parabolic aperture [56] **b)** Alternative holding structure, pylons and arms for the sandwich material panels with laminated thin reflectors

The patented collector with segmented aperture shown in Figure 75 was designed in 2009 by scientists of the DLR. A demonstration of the concept has not been done yet, constraining the present technical information to assumptions or results based on simulations. The main motivation of its design pursues an optimized optical performance and the implementation of less material, while enabling a large aperture of 6 m width.

The collector itself consists of a segmented aperture area, namely the segment *S1* and two more symmetrically built, *S2* and *S3*, on the outer ends; see Figure 76. The shape of these parabolic segments varies dependent on the focal length *f*, thus consisting of three different parabolas, which share the same focal point:

$$y(x; f_1, f_2, f_3) = \frac{1}{4f_n}x^2$$

The mirror in the middle *S1* has a short focal length of 0.9 m, while the adjacent segment S2 measures 0.6 m and the outer mirror S3 a focal length of 1.4 m. The segments are positioned in such a way that the light beams reflected on the outer sections can entirely pass through the gap between the main *S1* and the adjacent *S2* segments, which also are positioned so that their shading does not cover the area of the lower mirrors.

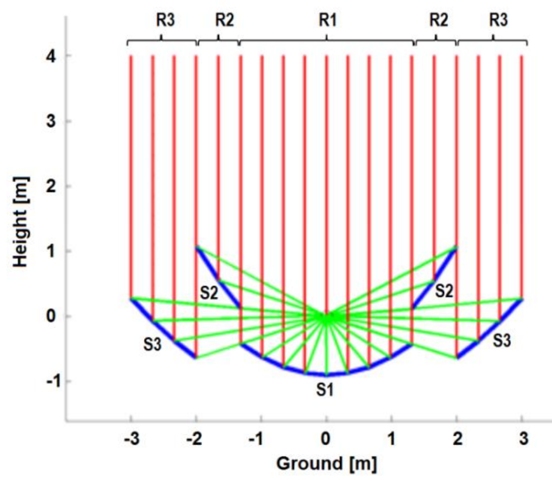


Figure B-37 Rays path on a cross-section of the fixed focus parabolic trough. Three mirror segments *S1, S2, S3* with the respective solar radiation fraction *R1, R2, R3* and common focal point are illustrated. The segment *S1* has a focal length $\boldsymbol{f_1 = 0.9\ m}$, the *S2* segments $\boldsymbol{f_2 = 0.6\ m}$ and the outer segment *S3* $\boldsymbol{f_3 = 1.4\ m}$. [57]

The compact positioning of the mirror enhances the intercept factor from 0.89[14] to 0.93 on an absorber tube of 70 mm diameter, because the reflected beams length is reduced. The improved optical performance results nevertheless at the expense of using more glass with a calculated increase of 19% compared to EuroTrough. The mirror facets have a similar architecture as in the Solarlite SL4600+ collector in section C1. There is a proposal to embed the reflectors directly to a fiber reinforced composite structure, filled with foam. By this method 30% of specific mass could be saved. The aperture dimensions per module are 6 m per 12 meter length amounting in 72 m^2 of aperture area [56].

In regard to the drive system, the concept proposes a decentralized configuration and rather a distribution of various units along the solar collector assembly. For example, this does not just reduce the rated torque required on the drives, but also the structures' stiffness, since the torque does not need to be transferred through the solar collector element over 50 m to 75 m longitude. These aspects correspond to a saving of material and costs, including the possible elimination of the flexible hoses or ball joints at each assembly end.

The concept aims also good resistance behaviour towards wind loads, as they flow straight forward through the collector's gaps. The following figure shows an example study of laminar wind interacting in zenith position of the collector:

[14] EuroTrough as reference

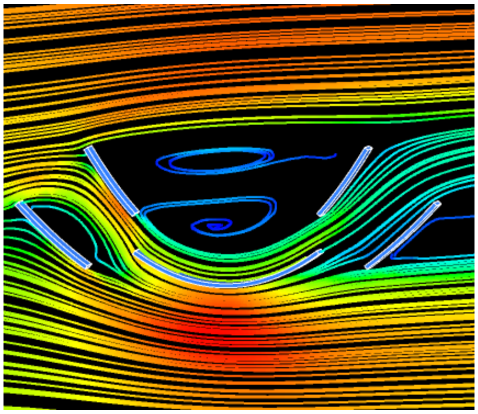
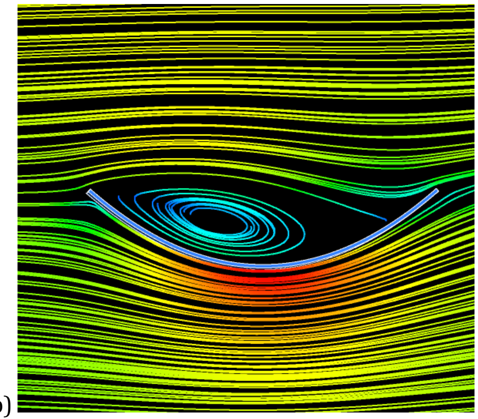
a)  b) 

Figure B-38 a) 2D CFD simulation of the segmented fixed focus collector aperture. **b)** An ideal parabolic aperture shape. Results and constraints of the simulation can be found in the following sources [35]

The result of a rough calculation shows a 20% drop of the solar field material costs in comparison to the EuroTrough [35].

An interview with the inventor of the concept pointed out challenges regarding the holding structure of the facets [58]. It should be configured as simple as possible; neither to cause an overburden of weight nor shadings on the aperture that could drop the collector's performance. Further aspects still require R&D, like the receivers´ interconnections, its heat collector element supports and bearings on the pylons to achieve longer assemblies.

In a development stage, while parabolic trough collectors are adapting to molten salts as heat transfer fluid, this concept possesses the potential to be considered as an alternative for future applications. Due to its stagnating advance in terms of practical realization, the collector concept´s performance and costs can only be described by numerical and analytical argumentations so far.

E4. MS-Trough (Molten Salt)

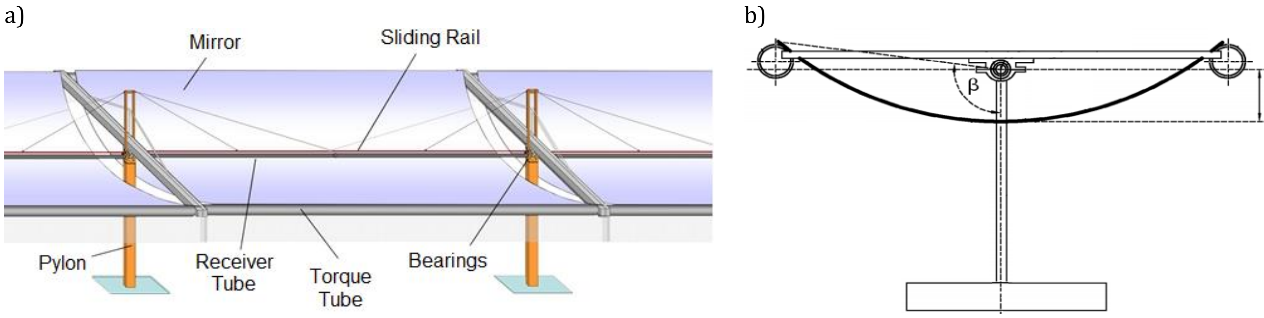


Figure B-32 a) MS-Trough collector and components with a fixed receiver along the modules [59] **b)** Note the two torque tube units at each end. They are built above the focal axis to locate the centre of mass at the rotary axis. The parabola possesses a rim angle larger than 90° and is characterized by a narrow mean focal length f_m. [60]

The MS-Trough is a fixed focus collector concept which targets an economic and substantial enhancement of the solar field´s efficiency. This collector contains particular features that enable the use of molten salt as heat transfer fluid. A real scale prototype of this collector has not been accomplished to date, for which the performance and costs information is attached to assumptions and feasibility studies conducted by experts. A scaled prototype (1:4) has been built to demonstrate the geometrical properties of the collector, and it still remains under development.

The intended dimensions of the aperture are between 6 m and 7.8 m for the aperture width and 12 m for the modules length. In total a solar collector assembly of 800 m to possible 1000 m length can be reached by a continuous row of fixed receiver tubes. Two key components for this realization are patented solutions: firstly, special bearings for the receivers are featured at the pylons, which function as a connection between the tubes and separate the static receivers from the movable collector shell. Secondly, these tubes are mounted under a continuous sliding rail between the pylons through the entire solar collector assembly; see Figure 78a. These elements compensated the thermal expansion of the tubes during operation.

An improvement on the overall efficiency is expected, thanks to higher operational temperatures with molten salts. For example, the wider and longer aperture avoids significant thermal losses, since less special molten salt receivers are used. That also increases the concentration factor up to 111 with a receiver diameter of 70mm at an aperture of 7.8 m. The continuous row of absorbers without the flexible transition and end joints could enhance the thermal and pressure losses. The lack of these dispensable elements compared to their application on the solar field could save about 8% of the specific solar field costs.

Besides, the positioning of the parabolic mirrors with a narrow mean focal length contributes to a good optical performance, since the reflected sun beams travel a shorter distance, reducing deviations until the focal point. The state of the art optical performance of ~75-80% can be achieved in combination with the geometrical facets´ accuracy. Thin glass reflectors of 1 mm thickness are used. They are intended to be used as a top layer in thin sandwich material panel with reinforced fiberglass and foam. For these reasons lightweight, stiffness and geometrical precision are the aims of this concept. The new approach of the facets is attached to some challenges in the manufacturing, which could be the volumetric change of the foam during the hardening process or else, possible mirror bumps. Both are rather topics for detailed engineering and both possible to overcome.

Figure 78b illustrates the location of the torque tubes above the focal line, which collaborates to the proper mass distribution of the design. Similar to a see-saw the torque tubes are connected by an arm with welded holders and turn in the middle around the centre of mass. Since the components' distribution allocates the centre of mass on the rotary axis, the collector remains at balance in any angular position. The structure itself also suggests a new kind of assembly, for which special jig assemblies would be required on site.

In regard to the drive units, the implementation of one drive for each 200 m collector row is intended. The drives are located at ground level would transmit the torque through a geared wheel in the structure as demonstrated with the scaled prototype. From here the torque transmission would be carried out by the torque tubes built at each end of the parabolic aperture, which also bring balance and stiffness.

The MS-Trough alone with the suitability of operating with molten salt as heat transfer fluid shows the potential of covering the demands on innovations requirement, with a further advantage of meaning an enhancement in the global efficiency of the solar power plant.

VII. Category F: Further Concept

F1. FC1 Foldable collector

Figure B-39 “The folding process (left) and stow position with least drag (right)” [61]

“With the FC1 collector an alternative to the existing collector types LS2 and LS3 has been created. It combines the proven qualities of these collectors (high efficiency and high durability) with the advantages gained by the folding wings, mainly the lower sensitivity to storms and the automatic cleaning system. The former allows for lighter and hence cheaper pylons and foundations, while the latter will lower the O&M costs due to the reduction of water and workforce requirements” [61].

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