STRUCTURAL OPTIMIZATION OF A LINE-FOCUSSING SOLAR COLLECTOR WITH STATIONARY ABSORBER TUBE

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Abstract

A preliminary study on a line concentrating solar collector with stationary absorber tube has revealed significant cost reduction and performance enhancement compared to state-of-the-art Parabolic Trough Collectors. To decide whether this so called Fixed Focus Parabolic Trough concept is worth continuing, a pre-design of the concentrator structure for such a collector must be investigated. In this paper, the effects of operating conditions represented by wind forces and dead load on the shape accuracy of the concentrator are determined via finite element method (FEM). An optimization procedure written in ANSYS is applied to determine appropriate geometry and dimensions of the structure to obtain best optical performance at lowest material consumption. To maintain a mean focus deviation of the reflected rays from the focal line of less than 6 mm under operating conditions, a specific weight of 14 kg/m^2 could be reached. As structural elements of the collector are located between mirror and absorber, ray tracing analysis is performed for one selected conceptual design to estimate the effects of blocking and shading on the optical performance. The ray tracing revealed a reduction of the optical performance due to blocking and shading of 27 % for an incidence angle of 45° compared to 0° incidence angle.

Keywords: line-concentrating solar collector, stationary absorber tube, optimization, FEM, ray tracing

1. Introduction

Like the majority of renewable energies, CSP research focuses on the reduction of the levelised cost of electricity to be economically viable. The largest cost reduction potential is seen in the solar field, thus in the reduction of its investment and operation and maintenance costs. In case of line concentrating systems like the parabolic trough and the linear Fresnel collector, wide range of designs and materials have been developed and tested to obtain long lasting, good-performing and economic collectors. However, there are few approaches towards a completely new collector design[1]. One approach is the Fixed Focus Parabolic Trough (FFPT), which combines the advantages of Parabolic Trough Collector (constant aperture with low difference between peak and annual efficiency) and Linear Fresnel Collector (stationary absorber tube, low susceptibility to wind loads) by deploying a stationary absorber tube in combination with a segmented mirror surface rotating around the receiver tube. Previous work [1] revealed the possibility for enhanced performance and reduced cost in comparison to state of the art Parabolic Trough Collector [2]. However in that preliminary study, only the optical properties of the mirrors surface and its susceptibility towards wind forces were investigated, while the collector structure and its mechanical properties have not been considered yet. The next step in the development of the FFPT collector is to pre-design a structure of a single collector module and investigate its mechanical properties under operating conditions with respect to material effort and optical performance. Finite elements method (FEM) and ray tracing are applied to perform these investigations.

The next subsections are a comprehension of the preliminary study [1]. Section 2 will present the implementation of the FFPT in the FEM model, the way loads representing operating conditions are applied

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[1] e.g.: http://www.suntrofmulk.com/download/suntrofmulk_brochure3.pdf (retrieved 2011-07-26)
http://www.lehle-gmbh.de/solar/solar-thermal_trough_system.html (retrieved 2011-07-26)
http://www.glasspoint.com/technology-advanced-lightweight-mirrors.html (retrieved 2011-07-26)

and which means to characterize the optical performance are considered. Since a large fraction of the collector structure is located between the absorber and the mirror, a ray tracing analysis is presented in section 3 to estimate the reduction of optical performance by shading and blocking.

1.1. State of the Art Line Concentrating Systems

There are two mature concepts for line concentrating collectors; the Parabolic Trough Collector (PTC) and the Linear Fresnel Collector (LFC). The main advantage of the LFC is the use of cheap flat glass instead of expensive precast glass. Furthermore, the absorber is fixed, thus rotatable tube connectors are not required. The optical efficiency of the LFC is approx 25 % lower with respect to the parabolic trough [3] due to cosine losses, blocking and shading. The less constant output of the Fresnel must be compensated for by means of a larger solar field and storage system. Due to mirrors located close to ground level, the LFC is less sensitive to wind loads, while the structure of the PTC must resist high wind induced torques and forces to maintain its optical properties. Because of its constant effective aperture, the PTC (compared to LFC) is characterized by efficient use of the beam irradiation also throughout the year. A combination of the advantages of both systems is the basis of a new shape of line-focussing CSP technology.

1.2. The Fix Focus Parabolic Trough

The main axis of inertia of any one-axis tracking solar collector must match the rotation axis to avoid torsion by static imbalance. If the rotation axis also matches the focal line, one obtains a line concentrating collector with stationary absorber tube. The Fix Focus Parabolic Trough is an approach for such a collector. It is based on the fragmentation of the mirror surface, so that a part of the reflected light has to pass a gap in the collector structure to reach the absorber tube. The mirrors as well as the supporting elements are arranged symmetrically with respect to the absorber tube, enabling a mass distribution so that focal line and center of mass coincide. The mirror arrangement facing zenith position is shown in Figure 1.

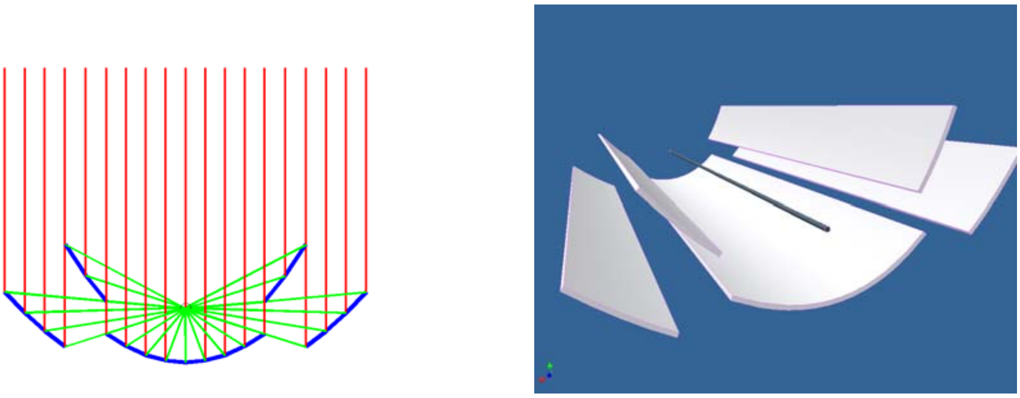

Figure 1: Mirror alignment of the fixed focus parabolic trough in zenith position. The mirrors (blue) consist of parabola fragments with distinct focal length and rotate as a unit around the focal line. Red lines indicate incident, green lines reflected sunrays. The structure to connect the segments is not shown. On the right is presented a 3D model of a module with 12 m length and 6 m aperture, including the absorber tube. The mirror surface consists of five so-called panels.

The reduced wind susceptibility of this structure and the improved optical performance[2] due to the reduced average length of the reflected rays was published in [1]. Further expected advantages of the FFPT are:

- Decreased specific weight due to reduced demands on torsion stiffness when decentralized drives are used
- Rotatable tube connectors (ball joints) can be avoided

On the other hand, several aspects have been identified as challenges for the implementation of the FFPT:

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[2] In comparison to state of the art EuroTrough geometry

- New designs are required for the support structure, tracking mechanism and especially compensation of the thermal expansion of the absorber tube.
- Commonly used precast glass mirrors attached to steel structure are not an option. To achieve the desired mass distribution, the mirror panel themselves must contribute to the rigidity of the concentrator. Self-supporting mirror with adapted mechanical properties have to be developed.

These challenges will be addressed in later research activities. The current work focuses on the fundamental question how the single mirror segments can be connected to each other and which deformation and thus optical performance under operating conditions can be achieved at a certain material effort. In the next section, an optimization routine will be presented. The goal of this routine is to find the lightest structure of the FFPT with the best possible optical performance. Based on these results, it is possible to decide whether the concept is worth continuing, sort of material effort and such cost can be reduced compared to state of the art PTC.

2. Structural Optimization

For the iterative optimization of the FFPT structure, a FEM model in ANSYS was created. Operation conditions as met by a collector in the solar field are considered as wind load and dead load. From the deformation caused by these loads, the optical performance in terms of the focus deviation in curvature direction (***FDx***) is introduced. The dimensioning of the structure is modified after every iteration until the desired optical performance is reached

2.1. The ANSYS model

A beam and shell FEM model (mesh width 5 cm) is used for the deformation analysis. To ease the comparison with the state of the art PTC as the EuroTrough geometry, the module dimension is set to 12 m length and 6 m aperture. The mirror geometry is obtained by extruding splines representing the parabolic shape of each mirror panel. A first approach for the structure connecting the mirror segments is presented in Figure 2. This approach consists of crossbeams connected to the edges of the mirror panels (blue). In such way, triangles are supposed to form a sufficient stiff geometry while the alignment would provide least blocking of the reflected rays. To avoid sagging of the outer panels, additional elements (red) were attached to take up tensile forces.

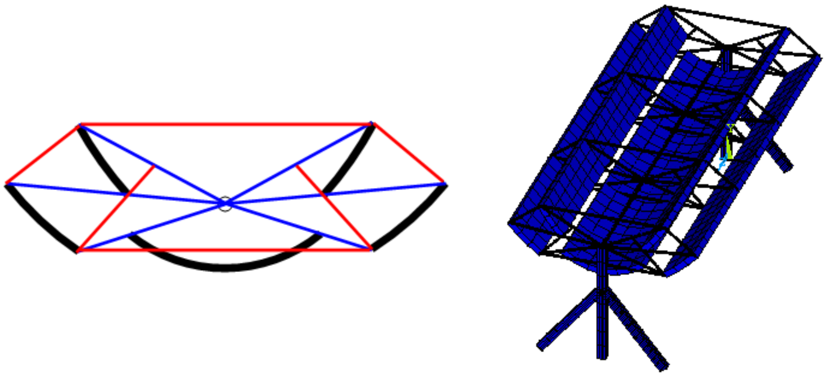

Figure 2: Cross section (left) and 3D view (right) on the FFPT as implemented in ANSYS. In the cross section view, red and blue lines represent the structural elements (cross beams) to connect the self supporting parabolic shaped mirror panels (black).

The crossbeams consist of hollow rectangular steel profiles with a wall thickness of 2 mm. The self supporting mirror panels are implemented as a sandwich structure with an EPS foam core and a top- and bottom layer of glass fiber reinforced plastics (GRP). Thin glass mirrors with thickness of 0.8 mm are applied on top of the sandwich structure. Pylons and the absorber tube are considered in the model; however they do neither contribute to the calculation of the mechanical properties nor to the weight calculation. The material properties and initial dimensions of the structural elements are shown in Table 1.

Object	Height [m]	Width [m]	Wall [m]
Cross beam	0.05	0.05	0.002

Object	Mirror [m]	GPR [m]	EPS [m]
Panel	0.008	0.002	0.2

Material	E [Pa]*10^8	ρ [kg/m^3]*10^3	ν
Steel	2100	7.9	0.30
Mirror	700	2.5	0.22
GRP	252	1.5	0.33
EPS	17	0.03	0.25

Table 1: Properties of structural elements. Upper left: Cross beam initial dimensioning. Lower left: Mirror panel initial dimensioning. Right: Young's modulus E, density ρ, and Poisson's ratio ν of the applied materials.

2.2. Considered Loads under Operating Conditions

Only zenith position was considered in the following investigations, since elevations close to zenith position represent the main contribution to the annual performance. The dead load was included by considering the gravitational acceleration. Wind load data was taken from former CFD calculations [1]. Here, the unobstructed incoming air flow attacks the collector module perpendicular to the longitudinal axis with a speed of 10 m/s at 10 m above ground level. The wind speed of 10 m/s was chosen since for a representative site (PSA), 96 % of the DNI are received under wind conditions below 10 m/s [4]. At this stage, only operating conditions and not the survival conditions[3] were investigated. The pressure distribution caused by the wind load and the resulting deformation from both dead and wind load are shown in Figure 3. The pressure distribution generates mainly a torque around the rotation axis/focal line twisting the entire module. The maximum deformations by wind load are about 5 mm at the outer right panels, while dead load causes a sagging of 2.5 mm in the center of the module with insignificant influence on the optical performance.

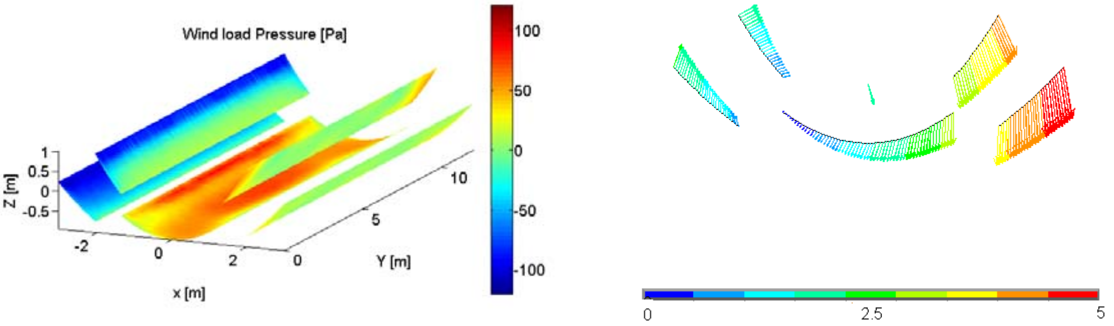

Figure 3: Left: Pressure distribution on FFPT resulting from lateral inflow from the left with 10 m/s. Right: cross section at y = 6 m, indicating value [mm] and direction of the deformation caused by wind and dead load.

2.3 Estimation of Optical Efficiency

The slope deviation in curvature direction (***SDx***) is a possible assessment criterion for the performance of CSP concentrators [5]. The slope deviation is defined as the difference between the slope of the deformed module under operating conditions and the slope of the ideal parabolic surface. For the calculation of the ***SDx***, the normal vectors of surface elements formed by the mesh of the FEM model were used. Since the allowable slope deviation depends amongst others on the distance of the point of reflection to the absorber, the deviation of the reflected ray from the focal line (***FDx***) is more convenient as boundary condition for the entire module. The ***FDx*** is derived from ***SDx*** and the distance between absorber and point of reflection (***s***):

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[3] Commonly represented by wind speeds > 30 m/s

$$FDx = \sin(2 * SDx) * s$$

The allowed mean ***FDx*** value for focus deviation caused by deformation under operating conditions of the entire module was estimated to 5 mm, assuming absorber tube diameter of 70 mm, aperture width of 6 m and a safety factor of two[4]. The mean ***FDx*** value is the average value of all five panels, while for each panel the RMS value of the ***FDx*** is calculated from all contributing surface elements.

2.4 Optimizations Methodology

For the optimization, the dimensions of the structural elements presented in Table 1 were defined as parameters to be varied, so-called design variables (***DV***), for which an upper and lower constraint must be set. The limiting value for the optimization is the optical performance represented by the ***FDx***. The ***FDx*** is a state variable (***SV***) with an upper constraint. The minimal mass is used as optimization goal, called objective function (***OBJ***). In every iteration of the loop, the design variables are varied and the state variable as well as the objective function are calculated. The optimization loop is repeated until the abort criterion specified by the user is fulfilled. The best design is the one that fulfills all constraints and obtains the smallest result for the objective function. If any of the constraints can not be fulfilled, the best design is the one closest to the constraints, irrespective of the objective function. For optimizing the structure, the sub-problem approximation method (SAM) of ANSYS was used. SAM is an advanced zero-order method where only the values of the dependent variables are required, but not their derivatives. Here, the same difficulties as in every multidimensional optimization apply: It is not necessarily the case that SAM terminates in the global optimum. In that case, a random tool for the generation of starting values or a parameter study is required to draw near the global optimum.

2.5. Results

Before starting the full optimization off all design variables, several parameter studies and part optimizations were carried out to identify those design variables that have a significant influence on the optical performance. In the part optimization, the panel thickness and the width and height of the crossbeams were optimized independently from each other. The dimensioning obtained from the part optimization was then used in the full optimization, were all parameters were varied. In Figure 4, the results of optimizations with different degrees of freedom and different constraints for the state variable ***FDx*** are shown.

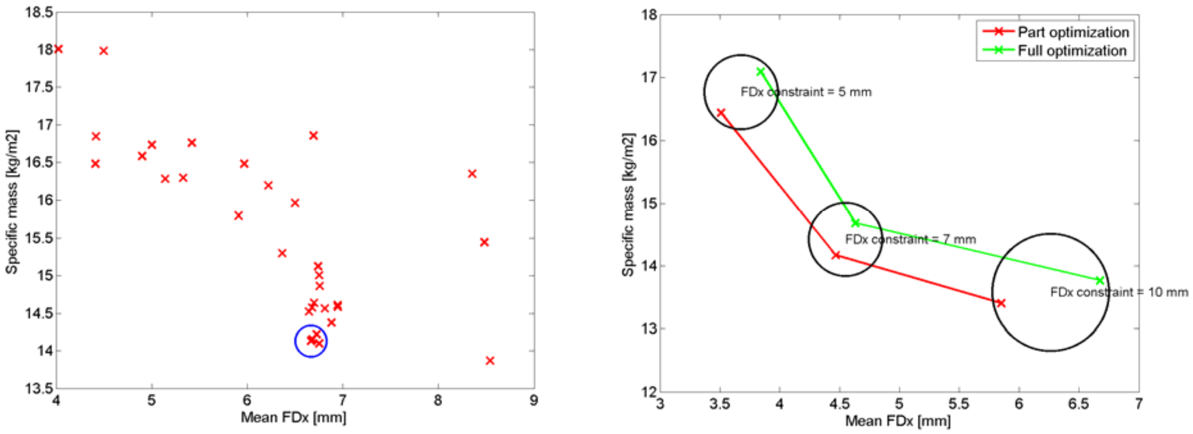

Figure 4: Left: Results for state variable (*FDx*) and objective function (specific mass) for a full optimization. After 40 iterations, the result flagged by the blue circle was reached. Right: Results obtained for different *FDx* constraints (5, 7, and 10 mm) obtained with part- and full optimization.

The best (lowest weight) results are derived for the part optimization, which means that the optimization

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[4] Since there are other deviations contributing to the ***FDx*** (assembly accuracy, tracking errors, etc…)

method did not succeed yet in finding the global optimum. Reducing the number of design variables and using a first order optimization method are assumed to solve this problem. In general, higher material effort delivers a stronger structure and such better optical performance. For a mean ***FDx*** of 5.9 mm, the total weight and its shares are presented in Table 2 and compared to values of the EuroTrough [2].

Specific mass comparison	EuroTrough	FFPT
Aperture area [m^2]	69.6	72
structure [kg]	1080 - 1312	775
Mirror [kg]	747	190
Specific mass [kg/m^2]	26.4 – 29.8	13.4

Table 2: Comparison of specific mass of EuroTrough and FFPT. In both cases, only the concentrator without absorber tube was considered. For the FFPT, the structure is made up by crossbeams and the substrate (sandwich panels) for the thin glass mirror.

3. Ray tracing analysis

PTC are designed in way that blocking and shading of incident and reflected rays cause no significant reduction of the optical performance. In case of the FFPT however, a major part of the structure is located between mirror surface and absorber tube. Thus, a careful investigation of the effects of these elements on the optical performance by means of ray tracing is advisable. For this purpose, the optimal structure regarding the specific weight returned by the optimization structure in ANSYS is implemented in the ray tracing tool SPRAY. No slope errors are considered in order to focus on the effects of blocking and shading. For increasing incidence angle, the projected surface of the structure on the mirror surface (shading) and on the receiver tube (blocking) will also increase. Hence, the total flux available on the receiver was calculated for various incidence angles and compared to the flux on the aperture plane. In Figure 5, an example flux map and the variation of power on the receiver and collector efficiency with increasing incidence angle are presented.

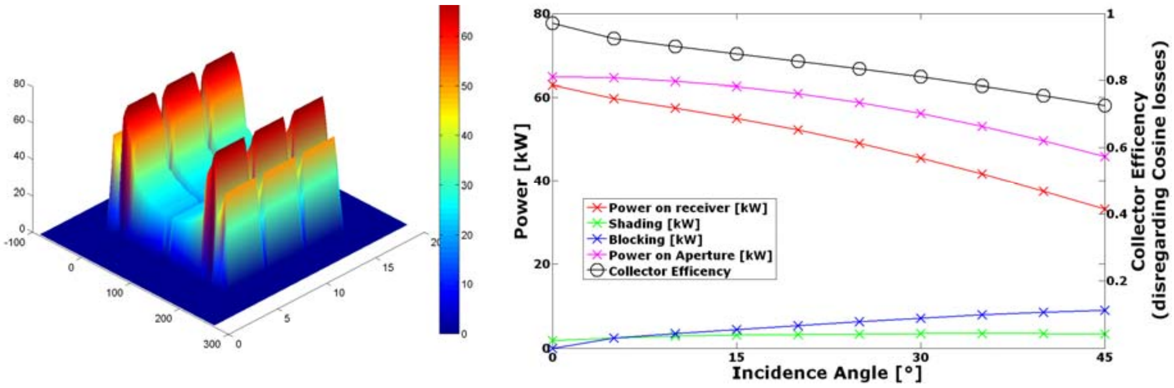

Figure 5: Left: Flux map [kW/m^2] obtained from ray tracing for the FFPT at 0 ° incidence angle. The gaps are due to shading of the structure. Right: Flux and collector efficiency vs. incidence angle. The collector efficiency is in this case defined as the ratio between power on receiver and power on aperture.

Reduction of the collector performance caused by blocking and shading of the crossbeams located in the path of light is significant for the particular conceptual design tested. While the loss in performance caused by shading remains constant with increasing incidence angle, up to 25% of the concentrated radiation is blocked by the structure for an incidence angle of 45°.

4. Conclusions

An optimization tool based on a FEM model for a new line concentrating CSP collector with stationary absorber tube has been developed and tested. One conceptual design of this collector has been investigated with this tool, determining its weight and optical performance under operating conditions, accounting for wind and dead load. With the dimension of the structural elements obtained from the optimization method, a ray tracing analysis was carried out in order to estimate the optical effects of the structural elements.

Comparison of the specific weight of the FFPT with the EuroTrough undertakes a weight reduction of approx. 50%. This weight reduction is achieved by the application of thin glass mirrors mounted to a self supporting substrate in terms of a sandwich structure. On the other hand, the properties of that particular conceptual design cause a relevant reduction of optical performance for increasing incidence angle. This reduction is generated by blocking and shading of structural elements located between mirror surface and absorber

The presented investigations were carried out to evaluate whether the FFPT concept is worth continuing. The potential of significant reduction of the specific weight could be confirmed. A reliable cost estimate is not possible at that stage of development. On the other hand, the performance decrease due to blocking and shading constitutes new challenges on the design of the FFPT.

5. Outlook

The obtained results are promising and suggest further research activities. Concerning the optimization tool presented in this article, the following improvements are manifest:

- The optimization algorithm should be modified to assure that the global optimum is found.
- The ray tracing result must be incorporated in the calculation of the optical performance and such integrated into the optimization procedure. Optimizing the structure only focusing on specific weight and mechanical stability in terms of minimal focus deviation without considering the optical properties of the structural elements will not achieve a feasible collector
- New approaches for the design and the structural elements are required to achieve acceptable values for blocking and shading with increasing incidence angle.
- In the current investigations, module dimensions of 12 m length and 6 m aperture width were used to ease the comparison with state of the art PTC. However, the potential of the FFPT concept could be fully exploited by increasing the module dimensions. The optimization should be repeated with different module length and aperture width

After obtaining a design from that enhanced optimization procedure, the next steps are:

- Including the 3D geometry in the FEM analysis to investigate local stress
- Creating a CAD model to develop a detailed design including joining elements for cross beams and panels
- Detailed engineering of striking aspects like drive, support, and compensation of the thermal expansion of the absorber tube.

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References

[1] C. Prahl, A. Pfahl, A new concept for line-concentrating CSP collectors, Proceedings of the SolarPACES conference 2009, Berlin Germany.

[2] E. Lüpfert et al, EUROTROUGH DESIGN ISSUES AND PROTOTYPE TESTING AT PSA. Proceedings of Solar Forum 2001, Washington DC

[3] M. Hoyer et al, Performance and cost comparison of linear Fresnel and parabolic trough collectors, Proceedings of the SolarPACES conference 2009, Berlin Germany.

[4] L. Amsbeck, Ermittlung des Strukturverhaltens und Optimierung eines neuartigen Heliostatenkonzeptes, Diploma Thesis, 2005, University of Stuttgart

[5] E. Lüpfert, S. Ulmer: Solar Trough Mirror Shape Specifications, Proceedings of the SolarPACES conference 2009, Berlin Germany, September 2009