# The Solarmundo line focussing Fresnel collector.
# Optical and thermal performance and cost calculations.

Andreas Häberle [a], Christian Zahler [a], Hansjörg Lerchenmüller [b], Max Mertins [b], Christof Wittwer [b], Franz Trieb [c], Jürgen Dersch [d]

[a] PSE GmbH, Christaweg 40, 79114 Freiburg, Germany,
e-mail: ah@pse.de
[b] Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2, 79110 Freiburg, Germany,
e-mail: lerch@ise.fhg.de
[c] German Aerospace Center (DLR) - Institute of Technical Thermodynamics, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany, e-mail: franz.trieb@dlr.de
[d] German Aerospace Center (DLR) - Institute of Technical Thermodynamics-Solar Research, 51170 Köln, Germany, e-mail: juergen.dersch@dlr.de

In the recent past different groups are intensifying the work on prototypes and industrial size collectors of line-focussing Fresnel collectors. The general idea of this type of collectors is not new. However the Belgian company Solarmundo attracted attention with their concept of a Fresnel collector that claims to be more cost effective than existing CSP-systems. Solarmundo operates a 2.500 m² prototype in Liège, Belgium.
The paper presents optical and thermal properties of the Solarmundo collector, which were calculated using Raytracing and computational fluid dynamics simulations. They are the basis for a simulation model to calculate the thermal output of the collector for different sites. The different behaviour of Fresnel collectors compared to parabolic troughs is discussed. An outlook on the achievable costs of electricity is given.

## 1. INTRODUCTION

### *1.1 The Principle of the Solarmundo Fresnel collector*

In the Solarmundo collector large fields of modular Fresnel reflectors concentrate beam radiation to a stationary receiver at several meters height. This receiver contains a second stage reflector that directs all incoming rays to a tubular absorber.

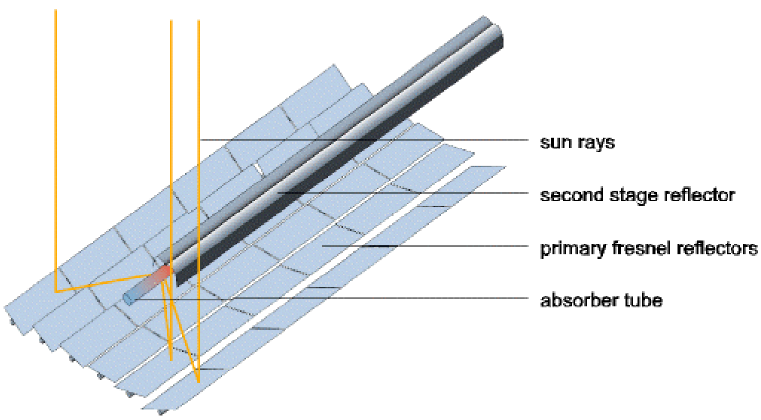


**figure 1: principle of the Solarmundo Fresnel Collector.**

The mirrors themselves, each having a width of 0,5 m, are not completely flat but have a very small curvature, which is achieved by mechanical bending. The collector consists of 48 rows of mirrors, which leads to a total collector width of 24 m.

The second stage concentrator not only enlarges the target for the Fresnel reflectors but additionally insulates the selectively coated absorber tube. To the back it is covered by opaque insulation and to the front a glass pane reduces convective heat losses.

The basic design of a whole collector field for direct steam generation is sketched in figure 2. The solar field for a 50 MW solar thermal power plants will be build up in 12 collector rows each with a length of 1000 m. The rows can be installed one close to another so the land use of the solar field is practically not more than the mirror area. The collector rows are linked in parallel and in series and the solar field is divided in three sections for preheating, evaporation and superheating.

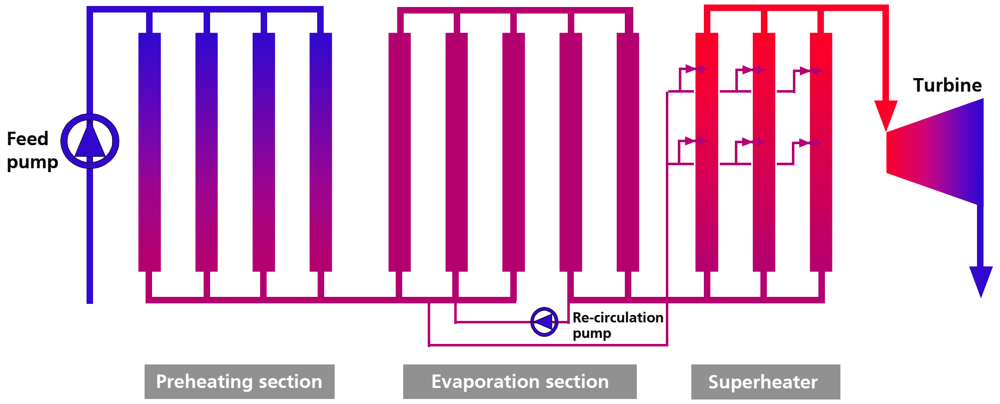


**figure 2: flow sheet of a collector field**

The main advantages of the Solarmundo Fresnel collector, compared to trough collectors are:

- inexpensive planar mirrors and simple tracking system
- fixed absorber tube with no need for flexible high pressure joints
- no vacuum technology and no metal glass sealing
- one absorber tube with no need for thermal expansion bows
- due to the planarity of the reflector, wind loads are substantially reduced so the reflector width for one absorber tube can easily be three times the width of parabolic troughs
- due to direct steam generation no heat exchanger is necessary
- efficient use of land since the collectors can be placed one next to the other.

According to Solarmundo these advantages lead to a cost reduction of about 50% for the solar field compared to parabolic trough. Cost reduction due to economy of scale and due to an optimal design of the collector will further reduce the investment costs for the solar field. In addition to the cost reduction in the solar field, there are considerable savings offered by lower operation and maintenance costs.

Compared to the Solar trough technology there is an additional application for Fresnel solar collectors, which at present is not evaluated systematically but might show future benefits: a controlled greenhouse can be implemented in the space below the mirrors. By using the diffuse light and the light reflected on the back of the mirrors (~300 W/m²), one can produce the ideal circumstances for the growth of shadow plants even in arid climate zones.

### 1.2 The Solarmundo Prototype

In 1999 Solarmundo started erecting a 2.500 m² prototype collector in Liège, Belgium for debugging the system and verifying its mechanical aspects.

**figure 3: 2500 m² prototype in Liège, Belgium**

The rare sunshine periods were used for operational tests of the collector and to gather experience with the tracking system. However, in order to test most of the mechanical aspects of the collector, no sunshine is necessary.

One key problem to be solved is to be able to ensure low maintenance under very harsh ambient conditions. Therefore the bearings and the driving mechanism of the mirror tracking was extensively tested in the laboratory. The bearings were developed together with the Bayer AG. Their asymmetrical shape adjusts the center of gravity of the mirror rows to their turning axis. This is necessary to achieve low driving forces.

**figure 4: asymmetrical bearings**

**figure 5: durability test of worm gear**

The Fresnel principle is very simple: because the relative movement of all mirrors is identical for the tracking, once they are positioned correctly, their movement can be mechanically coupled. Several mirror rows are driven by one motor. The mechanical coupling is done with a worm gear, which also is constructed in a way that sand and dirt can simply fall through. Both, the bearings and the worm gear drive were intensively tested and proved their ability to withstand years of operation with the continuous presence of sand and dirt.

The absorber tube has an inner diameter of 18cm and is welded at the construction site to its total length without the need of compensation bows. The thermal expansion is allowed for by mounting the tube on rails. The total movement due to thermal expansion in a plant of one kilometer length can be up to 6 meters at the end of one tube.
At the prototype a black (non selective) absorber was used, which is absolutely sufficient for the purpose the prototype is used for. In order to achieve satisfactory thermal performance however, a highly selective absorber coating must be applied, which has to be stable under non vacuum conditions up to high operation temperatures.

Solarmundo presented samples of a selective coating on a smaller absorber tube with both: very promising optical properties and a good durability in normal atmosphere. Currently they are working on transferring the coating to the 8 inch steel tube of the collector.

## 2. THEORETICAL PERFORMANCE OF THE COLLECTOR

Although the prototype collector was operated under real conditions and proved to produce steam, no thermal efficiency measurements are available yet. The optical and thermal performance has to be deduced from theoretical considerations. The aim of the here presented calculations is to give a theoretical estimation for the achievable optical and thermal efficiency of the Solarmundo Fresnel collector. Raytracing results were used to calculate the optical performance whereas the thermal performance was estimated using computational fluid dynamics (CFD).

### *2.1 Aperture, reflector area and gross area*

In order to compare trough and Fresnel collector efficiencies, a common reference area has to be defined. In the frame of the here presented work the aperture area was chosen as basis of all comparisons.
The aperture area of a parabolic trough is defined as the projection of its reflector area. The gross area of a collector field takes into account the space in between the troughs, which typically is two times the aperture.

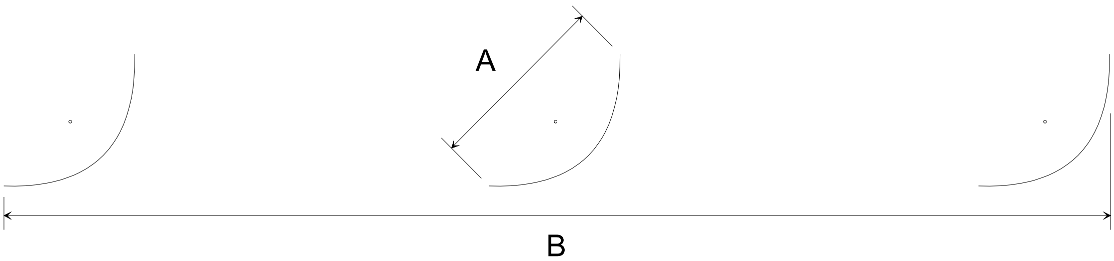


**figure 6: reference area of parabolic trough: aperture A, gross area B**

The aperture area of a Fresnel collector is almost identical to its reflector area, because the curvature of the single Fresnel reflectors can be neglected in this context. The gaps in between the single reflectors $d_i$ have to be added to the aperture area A to yield the gross area B.

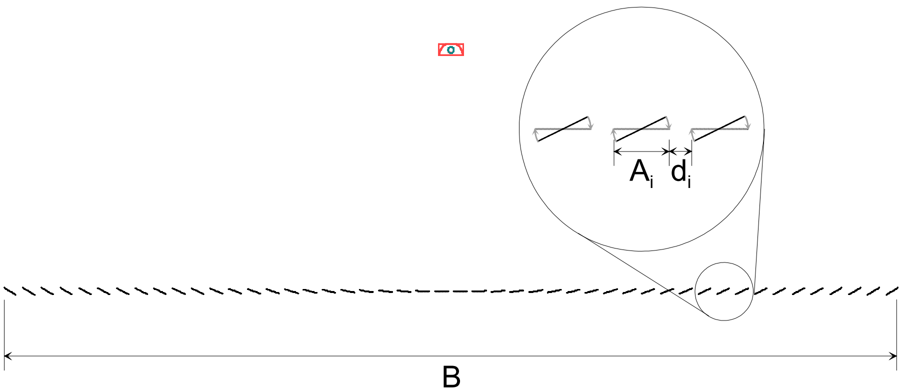


**figure 7: reference area of Fresnel collector: aperture A = $\sum A_i$, gross area B**

By definition the aperture of a trough is tracking the sun. The aperture of a Fresnel collector stays horizontally even though the single Fresnel facets are tracking the sun.

## *2.2 Optical Performance*

3-dimensional Raytracing calculations have been carried out with the program OptiCAD using the following material parameters.

**table 1: Material Parameters**

| | |
|---|---|
| reflectance of primary reflector | 92% |
| transmissivity of glass pane | 95% |
| reflectance of secondary reflector | 95% |
| absorptance of absorber tube | 94% |

Compared to earlier calculations [3] some ideal assumptions were looked at in more detail: Divergence of the beam radiation was included and assumed to be homogenous over a wide angular range to cover most of the circumsolar radiation. The reflectivity of the primary mirrors was modeled using a Gaussian scattering distribution and also the error of positioning of the Fresnel reflectors was assumed to be Gaussian distributed.

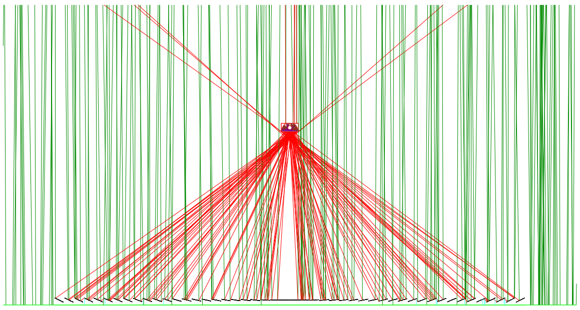

**figure 8: Raytracing (cross section)**

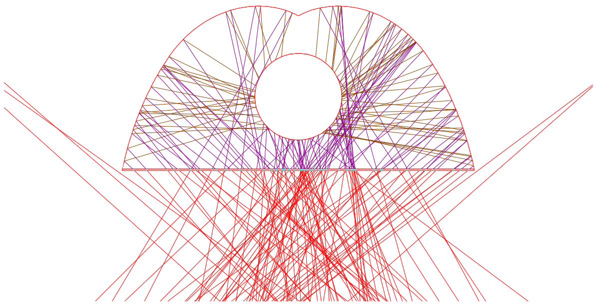

**figure 9: absorber and 2nd stage reflector**

Integrating the intensity of all absorbed rays at the absorber tube gives the result that for the given parameters and assumptions

$$\eta_0 = 61\% \tag{1}$$

of the perpendicularly incident radiation (e.g. at the equator at solar noon on March or December 21st) are absorbed and transformed into heat at the absorber surface. Doing the same for incident angles other than perpendicular and comparing the two gives the incident angle modifier IAM which is shown in figure 10.

$$IAM = \frac{\eta_0(\Theta)}{\eta_0(\Theta = 0)} \tag{2}$$

The incident angle modifier accounts for change in efficiency for incident angles other than perpendicular. It does not account for cosine losses of the normal beam radiation. The transversal $IAM_t$ is defined as the IAM in a plane perpendicular to the tracking axis. It is remarkable that the $IAM_t$ reaches rather high values for high incident angles. This is mainly due to the fact that for high angles of incidence less rays are lost in the gaps between the mirrors and less neighboring mirrors illuminate each others backside instead of the absorber (less blocking). The longitudinal $IAM_l$ is parallel to the tracking axis and is basically determined by the aperture glass pane of the second stage concentrator.

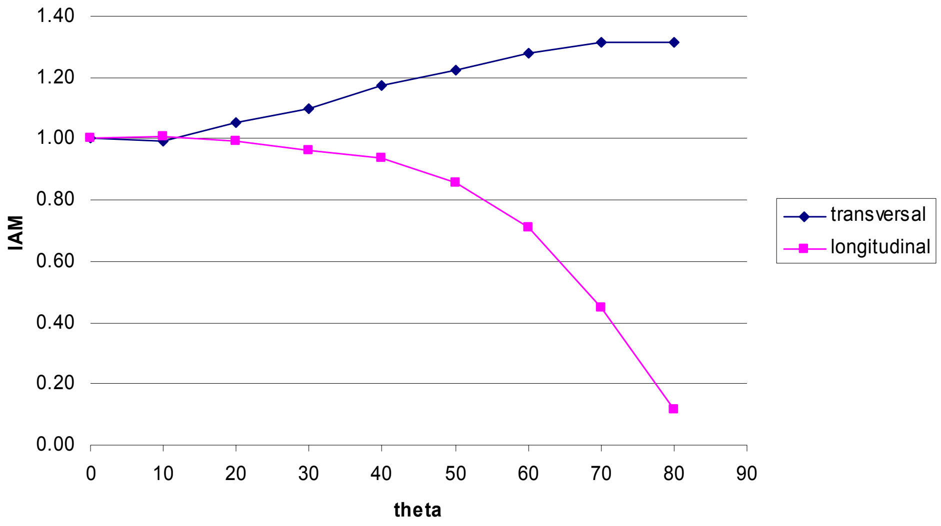


**figure 10: biaxial incident angle modifier**

One advantage of Fresnel collectors is the fact that the absorber is illuminated from underneath independently of the sun position. This is an advantage for the operation of a stratified two phase flow, where fluid is in the lower part of the tube and steam is in the upper part.
One outcome of Raytracing simulations is the relative intensity distribution at the absorber (see figure 11). It shows to be very evenly distributed (between 80% and 100% intensity) in the lower part and very low in the upper part of the tube. This pattern doesn't change significantly for different angles of incidence.

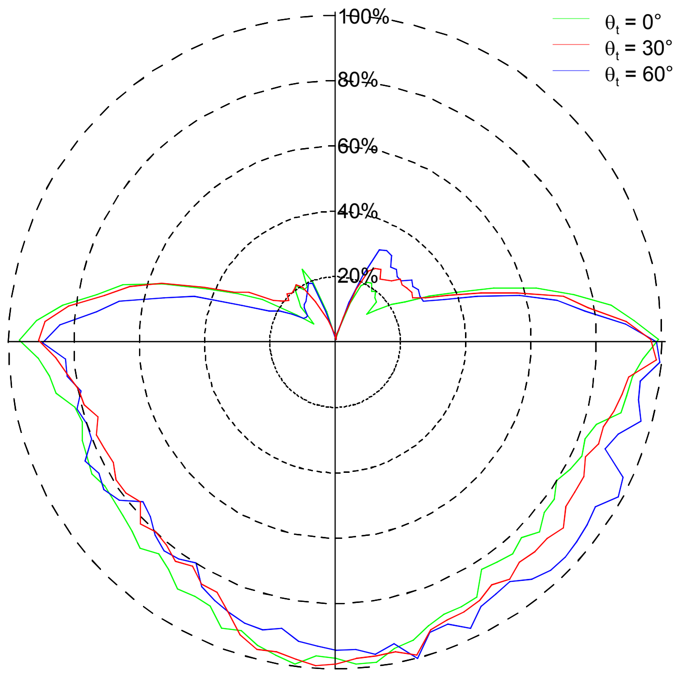


**figure 11: relative intensity distribution at the absorber for different incident angles $\theta_t$**

## *2.3 Thermal Performance*

To calculate the heat losses from the absorber tube, CFD simulations (FLUENT) were carried out which take into account all heat transfer mechanisms: radiation, convection, conduction. Apart from the general geometry a number of basic parameters are used as input.

**table 2: Material Parameters**

| | |
|---|---|
| thermal emittance of the absorber | 5% |
| heat transfer coefficient from aperture glass pane and backside of the 2nd stage concentrator to the ambient | 10 W/m²K |
| heat conductivity of backside insulation | 0.05 W/mK |

The convection flow and resulting temperature distribution between the absorber tube and the second stage reflector and glass pane was studied for absorber temperatures from 100°C (373K) to 600°C (873K) with constant ambient temperature at 30°C (303K).

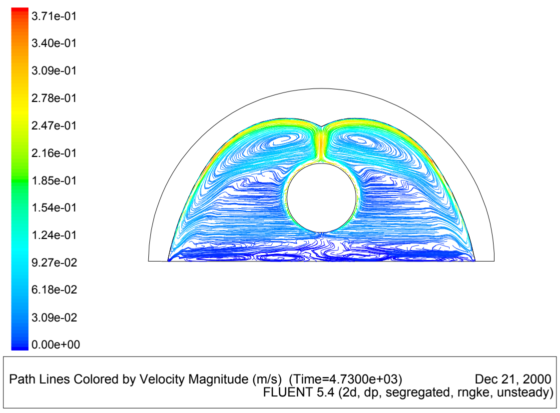


**figure 12: Convection path lines, $T_{abs}$ = 500°C**

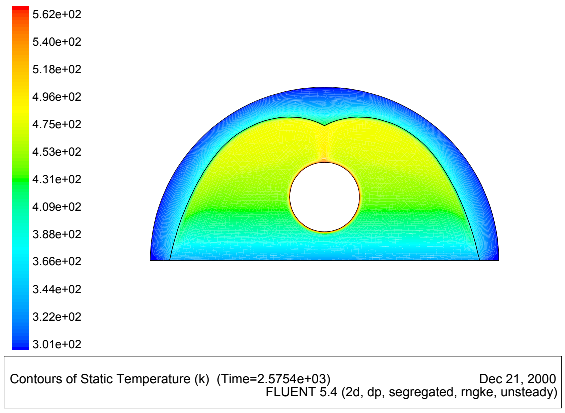


**figure 13: Temperature distribution, $T_{abs}$ = 500°C**

The resulting front and backside heat flux is given in the following graph in units of W/m of the absorber tube. As expected it shows to be strongly temperature dependant.

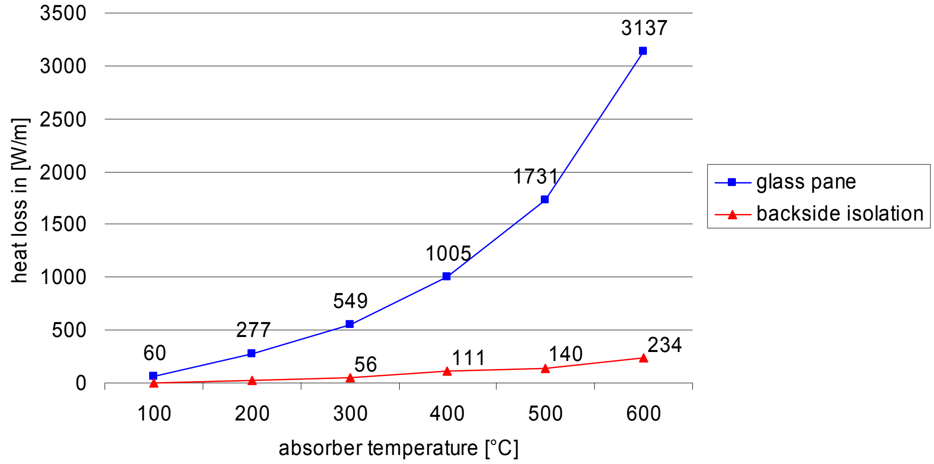


**figure 14: calculated heat losses to the front and to the back of the absorber**

The resulting temperature dependant heat loss coefficient per unit of aperture area is:

$$u = 3.8 \cdot 10^{-4} \cdot (T_{absorber} - T_{ambient}) \quad [\frac{W}{m^2 K}] \qquad (3)$$

*2.4 Efficiency Curve*

The following figure gives the resulting theoretical efficiency curve for vertical radiation ($E_{beam}$ = 800 W/m²) in dependency of the absorber temperature at constant ambient temperature ($T_{ambient}$ = 30°C).

$$\eta(T_{absorber}) = \eta_0 - u \frac{T_{absorber} - T_{ambient}}{E_{beam}} \quad (4)$$

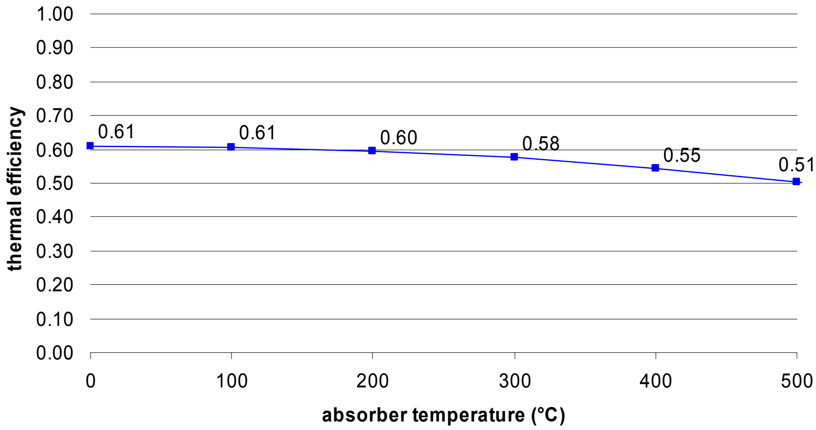


**figure 15: efficiency curve for vertical radiation**

It is important to note that the heat transfer from the absorber to the fluid has to be considered additionally when calculating the thermal output of the collector.

*2.5 Simulation Model*

For a first comparison of Fresnel and parabolic trough collector performance an existing and validated parabolic trough model in TRNSYS was used [2]. This parabolic trough model is an empirical model based on measurements at the power plants at California operated with a heat transfer fluid (HTF). The parameters used for this calculation are those of the new type of SOLEL collectors called UVAC [1].

The annual performance of a solar collector field with a design thermal output of 152 MW was calculated in hourly time steps. For the parabolic trough an aperture area of 261.600 m$^2$ and for the Fresnel system an aperture area of 336.700 m² was chosen, to compensate its lower efficiency. Solar radiation data for the Hurguada site in Egypt generated with the METEONORM software was used for the Fresnel collector as well as for the parabolic trough simulation. A north-south orientation of the absorber tubes was assumed for both systems.

The outlet temperature of the parabolic trough field was limited to 393°C to avoid decomposition of the HTF. For comparison reasons the same temperature was used as maximum temperature of the Fresnel collector. The usable part of the thermal power from the solar field was defined for both systems as all power between 38 MW and 152 MW. The upper limit comes from the design field output and the lower limit from the part load restriction of the steam turbine. 38 MW corresponds to 25% part load of the turbine. If the thermal power from the solar field is higher than the upper limit, the controller model defocuses sections of the field until the thermal output meets the desired value. If the thermal power from the field is lower than 38 MW all of the output is dumped.

The Fresnel collector was modeled in the simulation environment ColSim including the direct steam generation (two phase flow). ColSim is a simulation environment, which was developed at Fraunhofer ISE, initially to investigate different control strategies of solar collector systems. It is based on a plug-flow concept, where in each time-step a mass- and energy-plug passes the components according to a given flow path. Very small time-steps are possible so inertia effects can be calculated.

For the Fresnel model the optical performance and the heat loss characteristics were used as given above. Further assumptions were the neglect of steam slip and a thermodynamic equilibrium of the two phases. To estimate the thermal output of the three stage direct steam generation for a first approach the performance (mass flow at the demanded conditions) of each section was calculated in dependence of the solar radiation. Because of the different temperature level and enthalpy differences of each section the reachable mass flow varies. Due to the fact, that the mass flow at each section has to be identical, the section with the lowest mass flow limits the performance of the field. The other sections have to be defocused to adapt their power.

## 3. SIMULATION RESULTS

A comparison of the annual results for Fresnel and parabolic trough collector fields is given in table 3. All values are standardized to 1 $m^2$ of aperture area. The Fresnel system shows an efficiency of 34.5% based on direct normal irradiance, whereas the parabolic trough system exploits 50.1% of the Direct Normal Irradiance (DNI).

**table 3: Results of annual performance calculation for linear Fresnel and parabolic trough collector field at Hurguada (Egypt)**

| | Fresnel collector | | | Parabolic trough collector | | | |
|---|---|---|---|---|---|---|---|
| Direct normal irradiance | used Energy | lower limit dumping | upper limit dumping | used Energy | lower limit dumping | upper limit dumping | |
| 2782 | 958 | 41 | 44 | 1393 | 38 | 27 | kWh/m$^2$ |

In figure 16 the monthly values for both systems are plotted. There is no significant difference in the seasonal performance between the Fresnel and the parabolic trough collector.

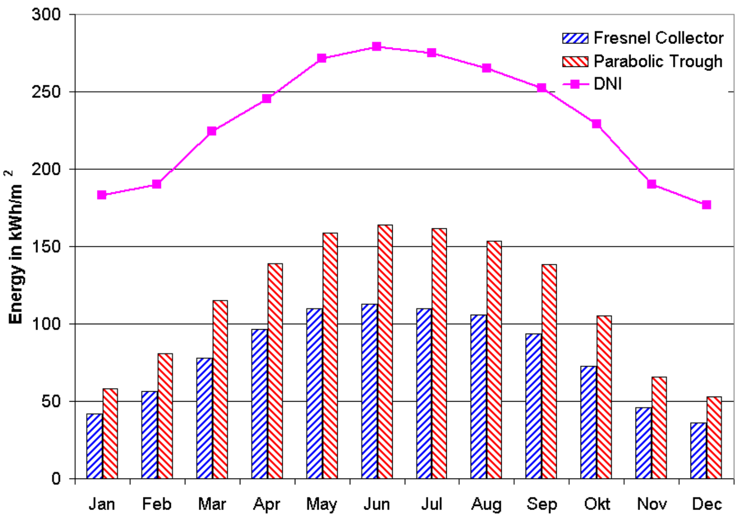


**figure 16: Monthly sums for the used Energy per square meter aperture for both systems compared to monthly sums of DNI at the Hurguada site**

In figure 17 a performance comparison for one single day is given. The date was chosen arbitrary, the only reason for this certain date was the occurrence of both kinds of dumping for both systems. This figure shows that the Fresnel system is specifically less efficient during the early morning and the late afternoon hours due to the flat incidence angles at the aperture.

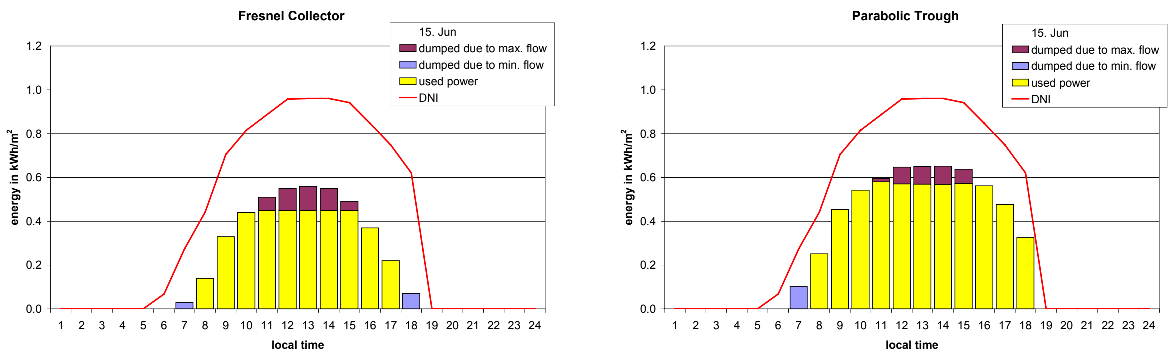


**figure 17: Performance of Fresnel and parabolic trough collector for one single day.**

## 4. COST OF ELECTRICITY

With the calculated values for usable thermal heat and with capital- and Operation & Maintenance cost (O&M), a first comparison for cost of electricity was made for the two different systems: Solar only power plant with Fresnel collectors and with parabolic trough collectors.

For the Fresnel collector cost projections on investment for solar thermal power plants have been made by Solarmundo. These projections lead to a specific solar field investment of 117 €/m². For the parabolic trough this investment was assumed to be 220 €/m² [4]. The investment for the classical part is taken equal for the Fresnel and trough system and insurance was assumed to be 1% of the direct investment. O&M costs were assessed for Egyptian salaries, for both systems with the same amount for O&M staff costs and a significant lower value for O&M material costs for the Fresnel system (less breakage due to wind loads and easier access to clean the mirrors).

With this input the cost of electricity was calculated with a simple economic model (see table 4). Although the efficiency of the Fresnel collector is considerably lower, due to the smaller investment the efficiency drawback is overcompensated and cost of electricity for the Fresnel system is even below the cost of electricity for the parabolic trough.

**table 4: Cost of electricity for linear Fresnel-collector and parabolic trough collector field at Hurguada (Egypt)**

| | Solarmundo | | Parabolic Trough | |
|---|---|---|---|---|
| **System Layout** | | | | |
| Rated Power | 50 | MWel | 50 | MWel |
| Power Block Efficiency | 33.0% | | 33.0% | |
| Collector Area | 336,700 | m² | 261,600 | m² |
| **Investment** | | | | |
| Power Block Investment | 34,832 | T€ | 33,993 | T€ |
| Specific Field Investment | 117 | €/m² | 220 | €/m² |
| Solar Field Investment | 39,401 | T€ | 57,552 | T€ |
| **Total Investment** | **74,233** | **T€** | **91,545** | **T€** |
| **Cost** | | | | |
| Interest rate | 6.7% | | 6.7% | |
| Economic lifetime | 28 | Years | 28 | Years |
| Capital Cost | 5,940 | T€ | 7,325 | T€ |
| Insurance Cost | 470 | T€ | 654 | T€ |
| O&M (Staff and Materials) | 1,570 | T€ | 2,184 | T€ |
| **Total Annual Cost** | **7,980** | **T€** | **10,163** | **T€** |
| **Yields/m²** | | | | |
| Solar Ressource | 1,171 | kWh/m²a | 1,752 | kWh/m²a |
| Usable Thermal Energy | 958 | kWh/m²a | 1,393 | kWh/m²a |
| Lower Dumping | 41 | kWh/m²a | 38 | kWh/m²a |
| Upper Dumping | 44 | kWh/m²a | 27 | kWh/m²a |
| Electricity Yield | 316 | kWh/m²a | 460 | kWh/m²a |
| **Total Yields** | | | | |
| Solar Ressource | 394 | GWh/a | 458 | GWh/a |
| Usable Thermal Energy | 323 | GWh/a | 364 | GWh/a |
| Electricity Yield | 106 | GWh/a | 120 | GWh/a |
| **Electricity Cost** | **0.0750** | **€/kWh** | **0.0845** | **€/kWh** |

## 5. CONCLUSIONS AND NEXT STEPS

The work presented here indicates that the Solarmundo Fresnel collector has about 70% of the thermal performance of a parabolic trough (UVAC) per aperture area. However, this lower performance is overcompensated by significantly lower investment and lower operation and maintenance costs of the collector field. With the cost figures of Solarmundo and the performance figures as calculated above, the resulting electricity costs of the Solarmundo Fresnel type collector are about 10% below the electricity costs of the trough system. Of course the trough system has the big advantage of being experimentally and commercially validated whereas the figures of the Solarmundo collector are only theoretical. This is why the next step for the Solarmundo collector must be a pilot plant under real operation conditions including commercial aspects.
Fresnel collectors have additional advantages like simplicity and making use of the land below the mirror fields, that might give further arguments in favor of this technology apart from the pure cost discussion.

## REFERENCES

[1] Barkai, Menashe; Ezer, Rami, Mandelberg, Eli; Frier, Scott; Gummo, Carin: Universal Vacuum Collector (UVAC) Proceedings of the Solar 2002 American Solar Energy Society Conference, Reno, Nevada, 2002

[2] Jones, Scott A.; Blair, Nathan; Pitz-Paal, Robert; Schwarzbözl, Peter; Cable, Robert: TRNSYS Modeling of the SEGS VI parabolic trough solar electric generating system Proceedings of the Solar Forum 2001, Solar Energy: The Power to Choose, Washington DC, 2001

[3] Häberle A., Zahler C., de Lalaing J., Ven J., Sureda J., Graf W., Lerchenmüller H., Wittwer V. The Solarmundo Project. Advanced Technology for Solar Thermal Power Generation. Solar World Congress 2001, International Solar Energy Society Conference, Adelaide, Australia, 2001

[4] Dersch J., Geyer M., Herrmann U., Jones S. A., Kelly B., Kistner R., Ortmanns W. Pitz-Paal R. Price H. Trough Integration into Power Plants - a Study on the Performance and Economy of Integrated Solar Combined Cycle Systems, 11. SolarPaces International Symposium, Zurich, Switzerland, 2002

## ACKNOWLEDGEMENTS

This work was co-funded by the German ministry for the Environment (BMU).