ROAD MAP TOWARDS THE DEMONSTRATION OF A LINEAR FRESNEL COLLECTOR USING A SINGLE TUBE RECEIVER

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Abstract

The new linear Fresnel collector technology shows the potential to reach significant market shares in the emerging global solar thermal power market. Our aim is to build and operate a full-size demonstration collector to gather experimental experience and test the theoretical expectations. In preparation for this, a series of analyses have been performed and component development is underway. We present here the recent progress within the project “VDemo-Fresnel” funded by the German Ministry of Environment, Nature Conservation and Nuclear Safety (BMU) under the number FKZ16UM0038.

The point of reference for this project was a Fresnel collector prototype installed in Belgium by the company Solarmundo. In this paper we present the results of the geometrical collector optimisations and the tracking system of the primary mirrors, and show results of the experimental evaluation of the receiver, including the secondary mirror. Models for direct steam generation in horizontal tubes have been investigated for the Fresnel collector. According to the simulation results, unfavourable flows can be avoided, and direct steam generation seems feasible. Mechanical loads on the absorber pipe have been analysed with an FEM-program under static conditions. The maximum stress in the absorber tube which occurs in the superheating section still remains below critical values. The infrastructural planning for the integration of the Fresnel collector at Plataforma Solar de Almería, Spain, has been carried out.

The main purpose of the “VDemo-Fresnel” project was the theoretical investigation and adaptation of simulation tools to the special technology of the linear Fresnel collector, in order to support the decisions leading to the building of a future demonstration collector.

Key words: Solar thermal power plants, linear Fresnel collector, demonstration, demo-collector

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Introduction – Background and Motivation

In the BMU-funded R&D-project “Technical and economical feasibility study on linear Fresnel collectors”[1] the Fraunhofer Institute for Solar Energy Systems, the German Aerospace Centre (DLR) and E.ON Energie AG laid the foundations for an independent evaluation of a linear Fresnel collector with a single tube absorber for application in solar thermal power plants. The collector concept was evaluated by developing and adapting simulation tools in order to calculate the energy yield and the costs of the collector. The main conclusion of the study was that the Solarmundo Fresnel collector (see figure 1, left), which was the starting point of the examinations, has a large technical and economic potential due to its large proportion of simple and therefore cost-efficient components.

In the course of this project questions arose concerning the receiver design, the dynamic collector/plant behaviour (respectively control) and the direct steam generation. Those questions were to be answered in the subsequent project “VDemo-Fresnel”.

Besides Solarmundo, a second company – Solar Heat and Power Pty. Ltd. from Australia – has also developed a linear Fresnel collector concept (see figure 1, right). Although the collector principle and size is similar to that of Solarmundo, it has several differences with respect to the size, construction and tracking concept of the primary mirrors as well as to the receiver design (multi-tube receiver). The evaluation of this concept in comparison to that of Solarmundo was also a task of the project “VDemo-Fresnel”. Solar Heat and Power Europe GmbH was part of the project team for “VDemo-Fresnel”. The main result of the comparison of the two collector types is that the technical and commercial maturity of the SHP collector is farther advanced. However, the study also established that the collector using the single-tube receiver (Solarmundo) has the potential to reach an energy yield which is 10% higher than that of the multi-tube-receiver.

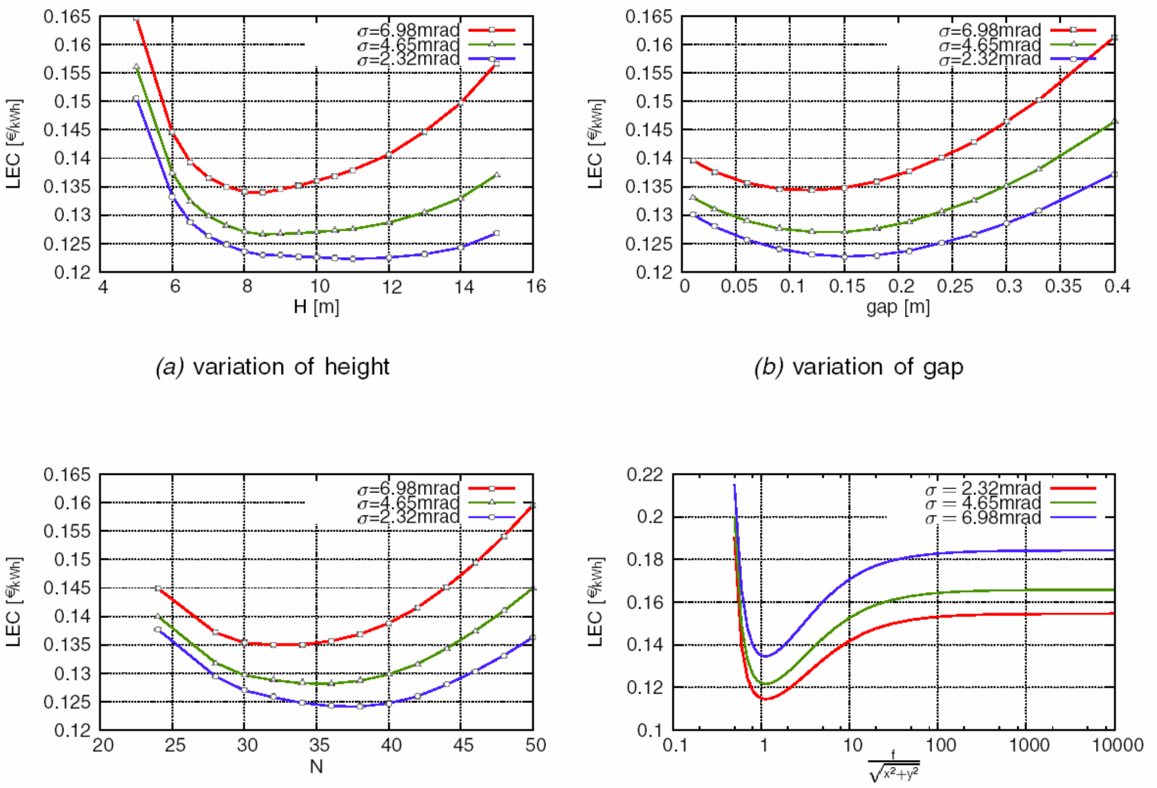
The further focus of the R&D-activities of the consortium was on the development and assessment of collector using a single-tube receiver. In the following chapters we present the main results of this assessment.

Figure 1: Prototype of the linear Fresnel collector by the Belgian company Solarmundo (left), Fresnel collector prototype by Solar, Heat and Power, Australia (right)

Collector Design Optimisations – Model and Results

Collector simulation tools were developed in order to calculate the optical, thermal and electrical energy yield of linear Fresnel collectors in power plants using the Fresnel collector as single or hybrid heat source.[2] Based, on the one hand, on assumptions of the cost structure of a linear Fresnel collector and using, on the other hand, optimising algorithms (e.g. evolutionary algorithms), the collector's size and geometry can be optimised with respect to ecomomic criteria, such as levelised electricity costs (LEC) (see figure 2).

Usually raytracing software is used for optical efficiency simulations. However, such calculations require large amounts of computing time, which represents a problem when many calculations have to be carried out for optimisations. Therefore, a new method was developed using statistical functions for sunshape, optical reflection errors, glass transmission, etc. Such distributions can be considered as independent statistical variables and are being convoluted into one effective radiance distribution that reaches the aperture of the secondary receiver. Some results of the sensitivity analyses are shown in the following graph. The different colours represent different assumptions on the optical reflection errors of the primary mirror field.[3]



(a) variation of height

(b) variation of gap

(c) variation of primary mirrors

(d) variation of the focal length

Figure 2: variation of geometric parameters – (a) variation of height of receiver above the primary mirrors, (b) variation of gap between the primary mirrors, (c) variation of number of primary mirrors and (d) variation of the relative focal length of the slightly bent primary mirrors, relative to the distance between mirror and receiver – (Reference design: Tube diameter 7.5 cm, number of primary mirrors: 34 (à 50 cm); receiver hight above primary mirrors: 7.5 m)

For the design optimisations described above one or more parameters must be fixed in order to optimise the other parameters. In our case the outer tube diameter and the shape of the receiver, including also the secondary concentrator and the covering glass plate (to minimise convection losses), were fixed.

In the simulations the issue of different tube diameters was also addressed. The scaling of the components' costs *C* (in €/$m_{collector}$) was addressed using the following formula:

$$C = C_0 (\frac{D}{D_0})^n$$

The wall thickness has a linear relationship to the tube diameter. Thus the steel mass has a quadratic relationship with the diameter. Therefore the tube costs are assumed to develop quadratically (n = 2) with the tube diameter. Coating costs for the tube (sputtering) will have an approximately linear relationship to the tube diameter (n = 1), because the capacity of the sputtering machine (number of tubes per load) depends linearly on the tube diameter. On the other hand, welding costs consist of a constant component (n = 0) because the number of welds will not depend on the tube diameter, however the length of the welding seam depends linearly on the tube diameter (n=1) which is why a value of between 0 and 1 should be assumed for tube welding. Such cost modelling was carried out for all relevant components. Besides the influence on the costs, energetical properties like optics, thermal losses and thermal inertia were taken into account. Depending on the cost assumptions – a tube diameter of 7 to 15 cm was calculated to be optimal.

Experimental evaluation of the receiver

A 4 m long receiver module was installed by the company Solar Power Group – that has emerged from the former company Solarmundo – in order to validate optical and thermal models of the receiver (see Figure 3).

Figure 3: Receiver using a single tube absorber (4 m in length) installed by Solar Power Group

A special optical method using bar codes was developed in order to measure the acceptance of the receiver. The experiments were designed to validate results from raytracing simulations (see figure 4).

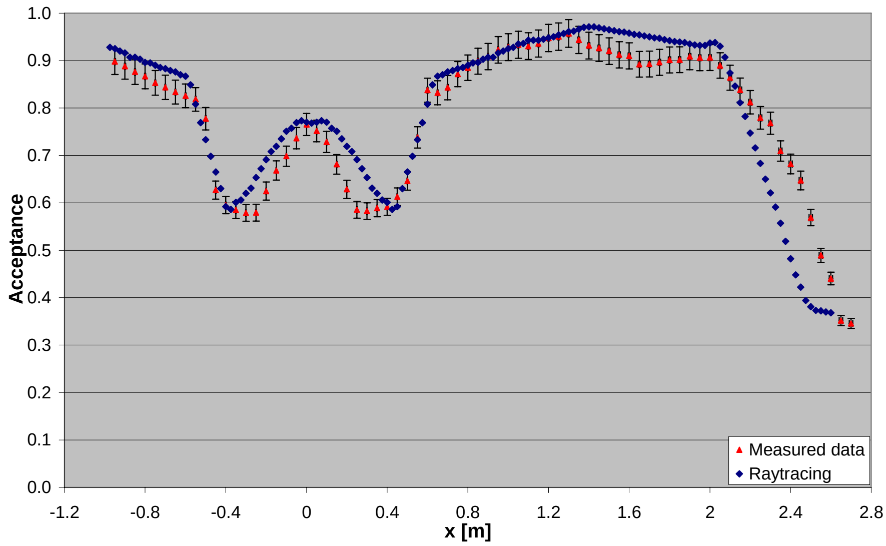


Figure 4: Receiver acceptance as a function of a transversal position 1.50 m below receiver - comparison of measurement and raytracing simulations

The comparison of the measurements and the raytracing simulation shows a good qualitative correspondence. The minor discrepancies result from the non-correspondence of the mirror shape with the ideal geometry (which results from prior theoretical optimisations) and from inaccuracies resulting from receiver assembly.

Direct Steam Generation in tubes with a large diameter

So far, direct steam generation has not been experimentally proven in horizontal tubes with a diameter larger than 10 cm. Therefore, direct steam generating models were collected and examined with respect to the suitability for linear Fresnel collectors.

For the description of the thermohydraulic conditions of the two-phase flow, the following parameters are of relevance:

- Operating pressure
- Fraction of steam
- Distribution of the heat transfer coefficients, depending on: 1) Flow pattern (Distribution of the phases / wetting angle of the tube), 2) Heat flux density, 3) Velocity of flow

Starting from a given set of parameter values (see Table 1) the following parameters and the corresponding effect on flow patterns were examined:

- Operating pressure (10-100 bar)
- Inner tube diameter (6-19 cm)
- Length of evaporator (100 m – 1000 m)
- Direct normal insolation (DNI) (400 -1000 W/m2)
- Steam fraction at collector outlet (50%-100%)

Parameter	Physical unit	Value
Operating pressure	bar	80
Inner tube diameter	mm	125
Tube length	m	1000
DNI	W/m^2	1000
Steam fraction (collector outlet)	-	0.85

Table 2: standard values for the parameter variation

The models used allow for an initial detailed analysis of the two-phase flow inside the absorber under static conditions. These theoretical examinations show, that unfavourable flows – such as stratified flows – can be avoided if the evaporator is adequately dimensioned (see figure 5). Therefore, we have no fundamental concerns about solar direct steam generation in linear Fresnel collectors, although the necessity of practical tests remains.

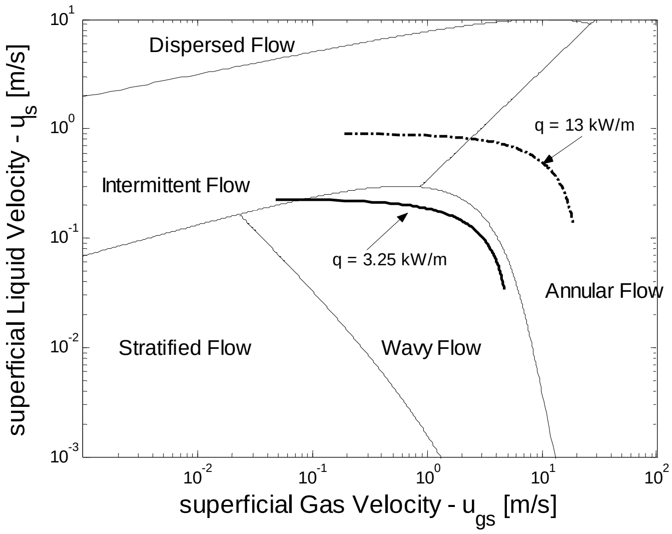


Figure 5: Taitel and Dukler flow pattern map for a water-steam flow in a horizontal pipe (p = 60 bar, D_i = 0,135 m) with the evaporation paths for a Fresnel collector for nominal insolation (13 kW/m) and low insolation (3.25 kW/m) (l_{evap} = 1000 m, x_{out} = 0,85).

Mechanical loads on the absorber pipe

Finite elements analyses were used to calculate the stress in the absorber pipe (see figure 6). The following influencing parameters were taken into account:

- Distribution of flux density over the tube surface
- Thermal expansion
- Force of gravity
- Pressure
- Friction due to different thermal expansion rates of various components (flexible overhead suspension)

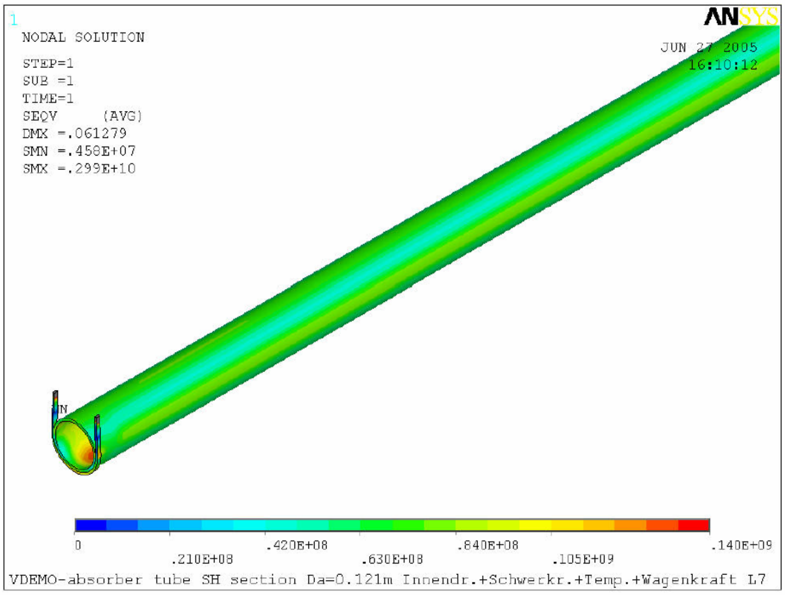


Figure 6: stress on the absorber tube resulting from fluid pressure, temperature, gravity and friction

The results show that the highest stress occurs on the bottom side of the tube. This results from a higher tube temperature at the bottom of the tube which leads to thermal expansion. The resulting stress accumulates together with the stress from the fluid pressure. On the upper side of the tube the thermal stress and the stress due to fluid pressure are in approximate state of balance. The gravity as well as the friction due to the flexible overhead suspension (trolley) have only minimal influence on the stress in the tube.

The highest temperature difference over the tube diameter occurs in the steam superheating section (50 K for a fluid temperature of 440°C). Therefore and because of the stress resulting from the high temperature, overall stress is maximal in the superheating section. According to our calculations, carried out under static conditions, the tube should withstand thermal stress for the lifetime of the plant (assumed at 100,000 h). But under real conditions there will be a low cycle fatigue caused by clouds passing the field and by the start up and shut down process of the power plant. Knowing these cyclic loads, it is possible to calculate the alternating stresses. In a next step, dynamic simulations of the Fresnel plants as well as measurements at a test collector will be necessary in order to make firm predictions with respect to the lifetime of the tube.

Tracking system of the primary mirrors

The control requirements of the Fresnel mirrors differ from the control of parabolic trough collectors in the sense that a large number of mirrors needs to be tracked. In principle several parallel mirror rows can be connected by using a mechanical coupling. However we came to the conclusion that individual mirror tracking leads to advantages due to its higher degree of accuracy. This concept has a high potential for cost reduction through the use of simplified and specifically adapted electrical motors and gears.

A test stand with several primary mirrors was erected in order to develop a system for tracking and position control with respect to fault tolerance, calibration, sensors, remote maintenance, cross-linking, protocols, cost and availability (see figure 7).

Figure 7: Test-stand for mirror tracking and control

The main findings and results are:

- The astronomic triggering is robust and highly accurate.
- Mirror drive could be realised with relatively low-priced components, suitable also for large-scale production.
- An automatic calibration routine was developed.

Planning of demonstration collector at Plataforma Solar de Almería (PSA)

One central goal of the project "VDemo-Fresnel" was the preparation of the installation of a fully functional demonstration collector to further develop the technology and to examine the technology's maturity. The demonstration collector must be suitable to examine, on the one hand, the mechanical, optical and thermal performance of the collector hardware, and, on the other hand, the operation and the control of the solar direct steam generation in horizontal absorber tubes with a large diameter.

Due to the planned length of one collector row of approximately 1000 m in commercial plants and the related high investment costs for a demonstration facility, compromises have to be made. Therefore, a concept was developed based on one Fresnel collector element with a total length of 100 m and a thermal power of approximately 560 kW_{th} which uses preconditioned water or steam provided by the direct steam generating parabolic trough collector (DISS) at the PSA. Qualified personnel is available at the PSA, which assures professional operation of the collector. Beyond that, the meteorological conditions at PSA are typical for a solar thermal power plant site in southern Spain.

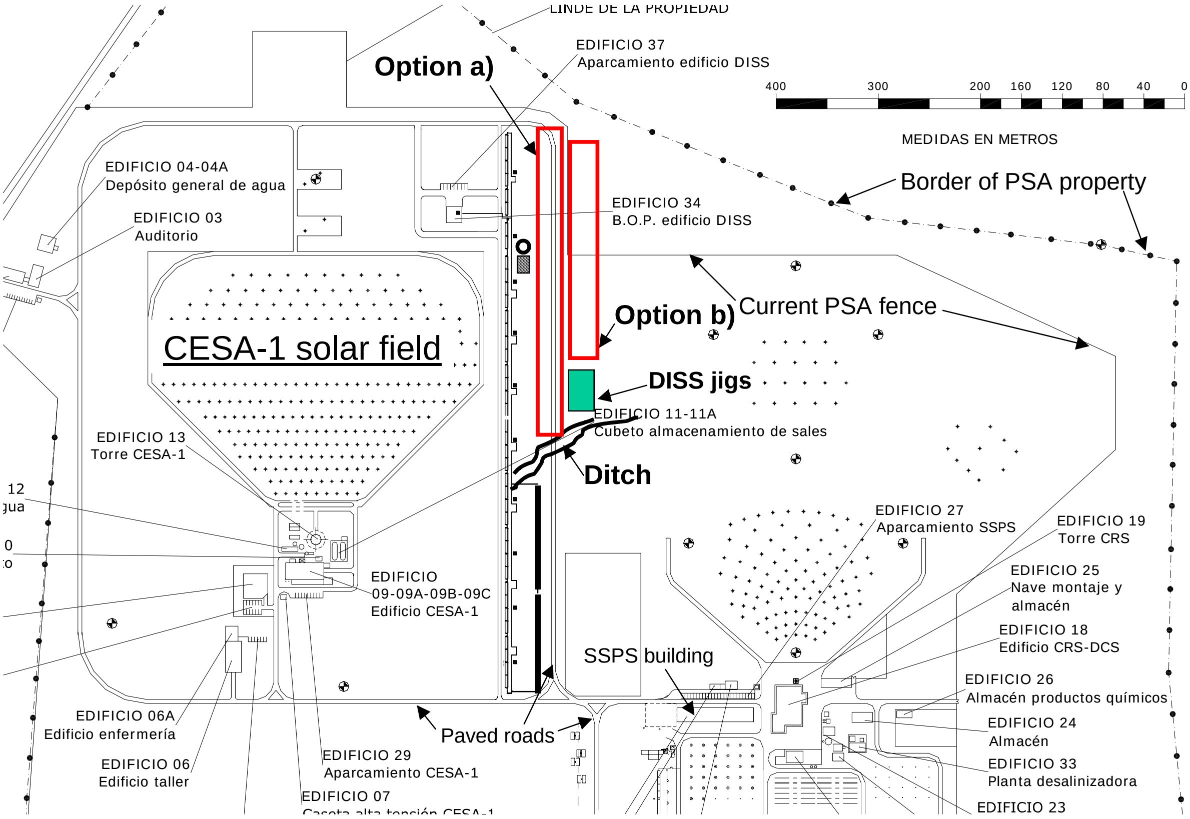


Figure 8: Options for the integration of the Fresnel collector into the facilities at the PSA

Infrastructural measures like determination of a precise collector position were carried out (see figure 8). Costs for those infrastructural measures, the installation of the collector and the measurement technique for the qualification of the collector were estimated.

Besides local and financial restrictions the decisive design criterion was to ensure a broad spectrum of possible real operating conditions. With the chosen collector dimensions the following issues can be addressed:

- The possible operation spectrum is: 1) full operation of the water preheating section, 2) the first 400 m of the evaporator under nominal mass flow, 3) the segments of high steam fractions can be operated in part load, 4) the superheating section can be operated in part load.
- The optical accuracy of the primary mirror field, including errors due to mirror reflectivity, mirror assembly, tracking and torsion can be evaluated
- The optical properties of other components as well as of the total system (incident-angle-dependent optical efficiency) can be determined
- The temperature distribution in the receiver and the heat losses can be determined under real conditions
- The interface of the control of the fluid (pump) and the mirrors can be developed and tested
- Mirror cleaning concepts can be developed and tested

Summary and Outlook

In this paper we have presented the energy and cost model of the linear Fresnel collector and results of sensitivity analyses. Experimental optical receiver characterisations were carried out in order to validate the optical receiver model used in the simulations. Models for direct steam generation in horizontal tubes have been investigated for the Fresnel collector. According to the simulation results, unfavourable flows can be avoided, and direct steam generation in linear Fresnel collectors seems feasible. Mechanical loads on the absorber pipe have been analysed with an FEM-program under static conditions. The maximum stress in the absorber tube which occurs in the superheating section still remains below critical values. The results of the development of a tracking system for the primary mirrors (soft- and hardware) have been presented. The infrastructural planning for the integration of the Fresnel collector at Plataforma Solar de Almería, Spain, has been carried out.

Subsequent to the work described in this paper, the collector components are currently being examined in more detail: thermal receiver tests are being carried out to determine the heat losses of the receiver using an electric heater inside the tube. These thermal receiver tests are also useful to determine the thermal stability of the receiver components. Furthermore, the reflecting properties of the primary mirrors are being currently examined in small scale. Such tests help to reduce the risk for a larger demonstration collector and future commercial projects. Beyond that, stable front surface mirrors with high reflectivity are being developed for use in secondary mirrors for Fresnel collectors but also for Solar Tower collectors. Air-stable absorber coatings which are to be used in Fresnel collectors are currently also under systematic evaluation and improvement.

The Fresnel collector has a large potential to generate solar electricity at comparatively low costs. However, the technology has to prove its technical and commercial maturity. Many of the assumptions in the collector models must be validated in future demonstration collectors and commercial plants. The next step for the commercial development of this technology must be a larger collector that is operated under real conditions.

Acknowledgements

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[1] Final Report of BMU-project “Technische und wirtschaftliche Machbarkeits-Studie zu horizontalen Fresnel-Kollektoren” – FK Fresnel-Kollektoren, Duration Dec. 01 to Aug. 03

[2] Software-Tool *ColSim*, developed by Fraunhofer ISE

[3] Detailed results in: Mertins M, Lerchenmüller H, Häberle A, Heinzel V: „Geometry Optimization of Fresnel-Collectors with economic assessment“; Conference Proceedings EuroSun 2004, page 1-918 to 1-925