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Low-cost Linear Fresnel Collector

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Content

1. Introduction

In this deliverable the design considerations for a Linear Fresnel Collector (LFC) of low-cost and high local content for the South African situation shall be described. The application considered in this case is an industrial application, where hot water or steam shall be produced by the collector, and typical solar field size is around 1000 to 2000 m2 aperture.
The main characteristics of the collector design are:
- low-cost in materials and construction
- high local content
- used for industrial applications up to 250 °C.

The components and materials for this LFC should come mostly from the hosted country. In the selection some emphasis has to be given to the tracking accuracy of the primary mirror and its driving construction and similar to the control system for the driving mechanism.

In the following the design goals are defined and motivated. Afterwards the goals are broken down into quantitative design specifications and requirements. From these specifications and requirements various prototypes can be developed.
The successful completion of the above three developmental stages will culminate into the testing and evaluation of the final prototype.

The overarching design goals are to create a solution, which is low-cost whilst maximizing the use of South African industry. Within this scope there are various other goals, which need to be successfully completed. These design goals are outlined in Table 1.

Table 1. Design goals for low-cost Linear Fresnel Collector

Design goal	Effected components	Expected results
Low-cost	All components	Solution is simple and cost-effective. Standard bought out components are favoured.
South African industry	All components	South African industries used wherever possible. Can easily be locally reproduced.
Single axis tracking	Actuators, control system, mirror structure	Support structure adequately supports mirror and driving mechanism. Deflections are within acceptable limits..
Tracking accuracy	Tracking algorithm, sensors, control system, mirror structure, drive system	Collector tracks with desired accuracy, the system tracks automatically.

Table 2 shows how the design goals can be further translated into a set of design requirements. “NEED” are the musts and “WANT” would be nice to get.

Table 2. Design requirements for low-cost Linear Fresnel Collector

Priority	Parameter	Specification	Design implication
NEED	Tracking	System needs track accurately	Mirror frame must be rigid. Control system and sensors must provide sufficient accuracy
	Low-cost	Maximise use of off the shelf components and low-cost components	System size is strongly dependent on supplier components (specifically for the mirror).
	Local industry support	Maximise local industry input	Local industries must be used where possible.
	Curved mirror	Mirror needs to curved	Mirror frame must be sufficiently rigid to facilitate mechanical mirror bending.
	Built on existing solar roof	System should fit into allocated space	Design footprint is limited.
	Automatic solar tracking	System runs automatically	Activation switch is only input.
	Withstand inclement weather	Results not affected after rough weather.	System must be sufficiently rigid and use an appropriate IP (Ingress Protection) rating.
	Safe	System should not pose direct or indirect harm to people, objects or itself.	Safety must be considered in all design and operation phases. Adequate IP rating applied.
WANT	Maintenance	All components	Components which require maintenance are easily accessible.
	Lightweight	Use of lightweight components used where necessary	Reduces need for extra support material and handling machinery.
	Complete mirror rotation	Full 360° rotation	Components with complete 360° rotational capability are selected.
	Lifespan	Design life will allow for future testing	Components with sufficient lifespan are selected and sufficiently protected.

2. Description of main components

Linear Fresnel Collectors have been extensively studied since more than 20 years, although the idea itself is much older and goes back to ASDASDAS [1].

2.1. Primary field

The primary field reflects the light onto the receiver. The mirrors are located at the level of the ground and are driven by a tracking system in order to effectively concentrate the light. The mirrors are manufactured to achieve high optical performance. High optical performance means solar reflectance value approaching unity, and a Gaussian beam spread due to nonspecularity and slope errors of less than 2 mrad. Ideally, the reflector must be cheap, durable and requires low maintenance. It is expected a life cycle of the reflector of at least 20 years under the harsh conditions of the desert. State-of-the-art reflectors have a specular reflectance of 93 to 94 percent and expected life of 20 to 25 years without excessive degradation [2].
The reflectance of glass mirrors is related to the content of iron oxide in the glass which protects the mirror surface (metallic Silver or Aluminum). A very high reflectance can be achieved by using low-iron white glass in the mirror production – which absorbs negligible energy in the infrared spectrum- typically less than 1% for a 3-4mm glass thickness. In mirrors it has been taken into account that the reflected light is transversing the glass twice, thus the absorption nearly doubles. For solar applications it is therefore desirable to use glass with low-iron content. Another possibility is to use thin sheet glass (with less about 1mm thickness) This glass is more fragile. Both improved glass products are generally more expensive on the market than the ordinary float glass used for mirrors. Thus the design question is whether the reduction in optical performance of about 5-10% (depending on the mirror glass thickness) is compensated by the lower cost of the component.
Other considerations are whether mirrors not based on glass can be used. Aluminum sheets with or withoug coating, polymeric films with coatings, and steel sheets have been proposed. In principle aluminum sheets coated with mirror coatings based on Silver are highly refective, but also very sensitive against dust (scratching of surface), a destruction of the necessary protective layer and thus deterioration. Other aluminum based refelction devices have the lower reflection characteristics of Aluminum compared to Silver. Even with perfect surface quality (polished) the reflectance of these mirrors is below 90%.

2.2. Receiver

The receiver is composed by the absorber surface, the secondary concentrator, the glass plate or envelope and the casing. Different configurations have been implemented for the Fresnel collector. Figure 1 shows the most common configurations

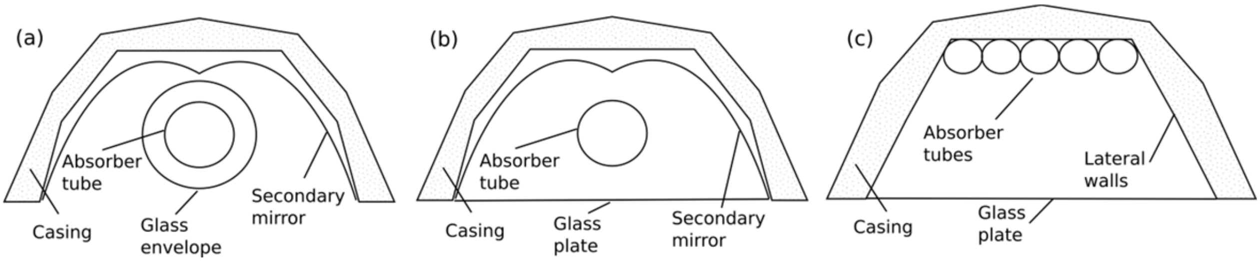

Figure 1 Common receiver configurations used in Linear Fresnel collectors. a: Secondary concentrator with absorber tube glass plate on the bottom. b: Secondary concentrator with absorber tube and glass plate. c: Row of tubes inside a cavity.

Although multi-tube receivers have an advantage when single end connection of a collector string to piping is considered, also the preheating and direct evaporation of water can be daone in a way to utilize the focal intensity distribution, we will not consider this option in the following. The reasons are

- Complex operation with different expansion due to thermal gradients
- Risk of ill-matched flow through the parallel receiver pipes
- Collector considered is small, so one-sided connections is not paramount

2.3. Absorber

The energy reaching the absorber must be efficiently conducted to the heat transfer fluid. Main energy loss mechanisms of the absorber are reflectance of incident light and thermal loss by convection and long wavelength radiation. Convections losses depends mainly on the temperature of the absorber and the surrounding conditions, therefore the absorber is protected with glass envelope or glass plate, as it is shown in Figure 1.

The operation temperature of the absorber surface in solar applications varies between 40 °C and 500 °C (313 K and 773 K). The effective temperature of the sun is approximately 6000 K. The infrared spectrum overlaps slightly the solar spectrum. Therefore it is possible to develop selective surfaces that have high absorptance for radiation in the solar energy spectrum and low emittance in the infrared spectrum. The ideal surface (Duffie, Beckman 2006) and its properties are represented in Figure 2

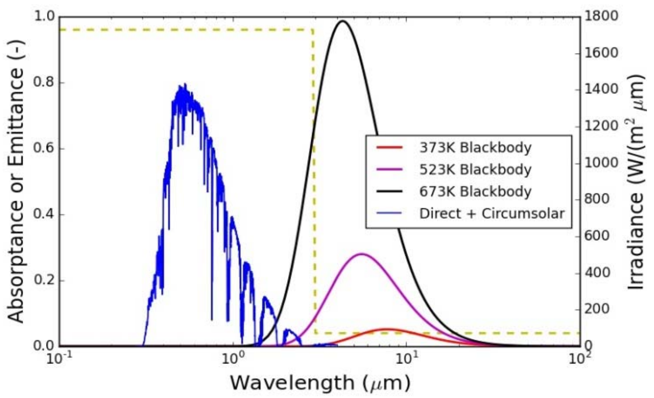

Figure 2: Relation between absorption and reflection at various wavelengths for solar absorbers. Own elaboration based on [3]

In the design considerations it is important whether a selective absorber with low-emissivity is needed for the application considered. A black surface is much cheaper to produce, and also local manufacturing of a low-tech variant is possible, whereas selective surfaces need high-volume production and specialized manufacturing processes (usually nowadays physical vacuum deposition , as galvanization is considered as a dirty process). This consideration is supported by the observation that the average receiver temperatures are much lower than for collectors used in solar thermal electricity production. Therefore the temperature dependent emission of therm al power (Stefan-Boltzmann law) is much smaller.

2.4. Glass cover or glass envelope

The glass aims to protect the absorber surface from direct contact with the environment. The glass protection can be either a plate or an envelope (see Figure 1). In terms of heat loss, the protection suppresses forced convection and shields the absorber from wind. In vacuum receivers, the space between absorber and glass protection is evacuated. Evacuated receivers have been developed only with cylindrical glass envelope and not with a glass plate due to the mechanical stability problem: a fixed glass plate with a pressure difference between interior and exterior of nearly one atmosphere would break. Evacuated tubes suppress convection completely. An additionaly benefit is that the environment is harsh for the absorber tube (especially the selective absorber coating) and the glass envelope protects the absorber tube from dust and humidity. Although there are novel coatings that are stable not only in vacuum, it is better for the longterm performance if deposition of dust and corrosion is inhibited. However, the glass absorbs and reflects a part of the incident radiation, thus decreasing the optical efficiency of the collector. When glass contains iron oxide which is the case in almost any flaot glass production due to the use of sand as raw material containing iron, it absorbs energy in the infrared spectrum- typically about 5% for a 3-4mm glass thickness. For solar applications it is therefore desirable to use glass with low-iron content. However this glass is generally more expensive on the market, as the requirements on the raw material are more strict, and secondly the production volume is much smaller than for the ordinary float glass mass product. Thus on question in the design could be whether the reduction in optical performance of 5% is compensated by the lower cost of the component.

2.5. Secondary mirror

The secondary mirror redirects the light that does not hit the absorber directly back to it. Its design is often based on non-imaging optics principles, as it is shown in Figure 3

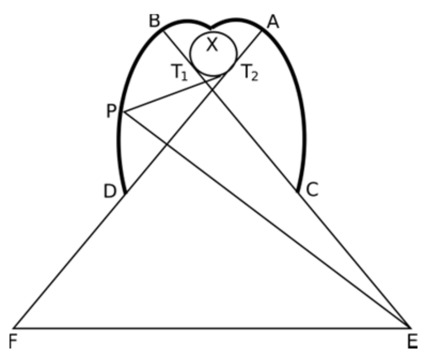

Figure 3 Representation of the ray-edge principle used to design the secondary mirror. Line FE represents the light source (primary field) for the design of the secondary mirror.

The-edge ray principle for a Linear Fresnel collector considers the primary field as a distributed light source. Taking the target as a tube, the resulting shape is a compound macrofocal ellipse [4].

The properties for secondary reflectors are the similar to the ones for the primary field, although the operation conditions are different. The secondary mirror is exposed to higher energy fluxes compared to the primary mirrors. Therefore its materials must withstand higher temperatures. The distribution of incident radiation on the secondary is not constant, with the consequence of temperature gradients along its transversal plane. Under these conditions, the secondary mirror must retain its shape and optical properties. Secondary mirrors are made from coated aluminum, steel or silvered glass. The glass bending needs more effort and leads to higher costs, but also the shape distrortions of bent aluminum or steel sheets should not be underestimated.

2.6. Casing

The casing provides stiffness to the complete receiver including absorber tube and the secondary mirror. It is the joint element between the structure and the components of the receiver. In configuration a) in Figure 1 the space between the secondary mirror and the casing can be insulated. If foam is used a rigid sandwhich type compentent could be produced. The insulation aims to decrease the heat loss, which has the indirect consequence of higher temperatures over the secondary mirror surface. Insulation in configuration b) does not have significant effects in the heat loss. The design of the casing must be such that allows the replacement of the absorber if it is needed and allows the expansion of the absorber and secondary mirror. At the same time, protects at least one side of the secondary mirror from the ambient conditions.

2.7. Structure

The structure provides not only the support to all functional elements like mirrors and receivers, it gives also more stiffness to the collector. It supports the primary field and the receiver. The relative location between the primary field and the receiver is fundamental for the precise concentration of light and the mutual shading and blocking of rays by neighbouring mirror rows. . The frame can be made of galvanized steel or aluminum. The assembly may be done with screws, bolts, rivets and welding or by more advanced and special connection methods. The structure is connected to the ground by foundations. Usually, foundations are made from concrete [2]. But in some cases with suitable ground earth poles or screws can also be used.

The structure has a considerable contribution to the collector weight. Ideally it has to be light to reduce material cost as much as possible, but it should able to provide the sufficient stiffness to the collector. The shadow over the primary field has to be minimal. There are three designs that have dominated the market. Figure 4 shows a sketch of these designs

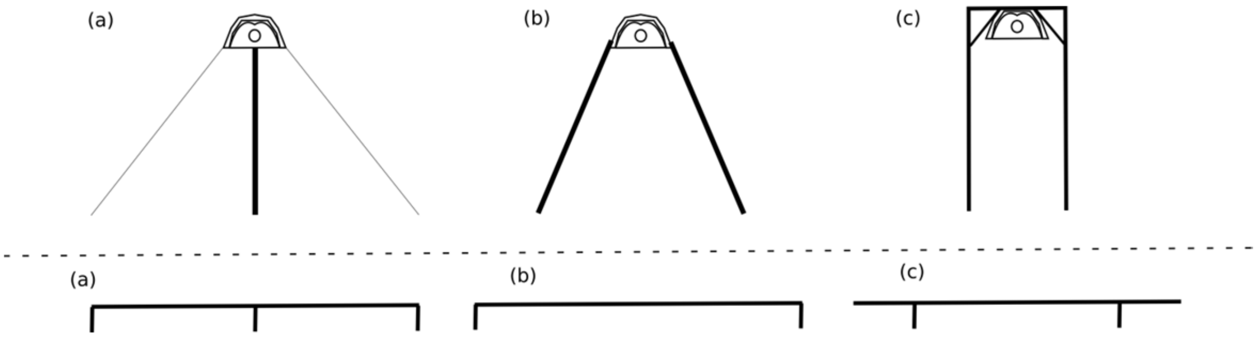

Figure 4 Front view of design options for the collector structure. Top) Support of the receiver, a: central pylon and lateral tensors, b: two pylons in angle (A shape), c: two pylons in rectangular shape. Bottom) Support of the primary field and connection to the ground, a: three foundations located at the extremes, b: two foundations located at the extremes, c: two foundations located symmetrically.

2.8. Tracking system

The primary field tracks the sun to reflect the light onto the receiver. The tracking system is in charge of moving the mirrors of the primary field. It is usually mounted on a base structure. It must be precise and durable under harsh conditions. The expected life is comparable to the one of the primary field (between 20 and 25 years).
Ideally the orientation of the collector is north-south along the longitudinal plane. In this case, the tracking system follows the apparent movement of the sun from east to west. The angular change for all mirrors is the same, meaning that one device can move all mirrors in the transversal plane. The design principle is to have one actuator that turns all mirrors (in the transversal plane) by means of a mechanical coupling. There are designs that use many actuators, allowing more flexibility in the collector operation (e.g. some rows can be defocused to better control the outlet temperature). The decision is a cost-benefit trade off. Figure 5 shows a sketch of these options.
The tracking system should be able to be adapted to latitude, to orientation of the collector, and in some cases even to a tilt.

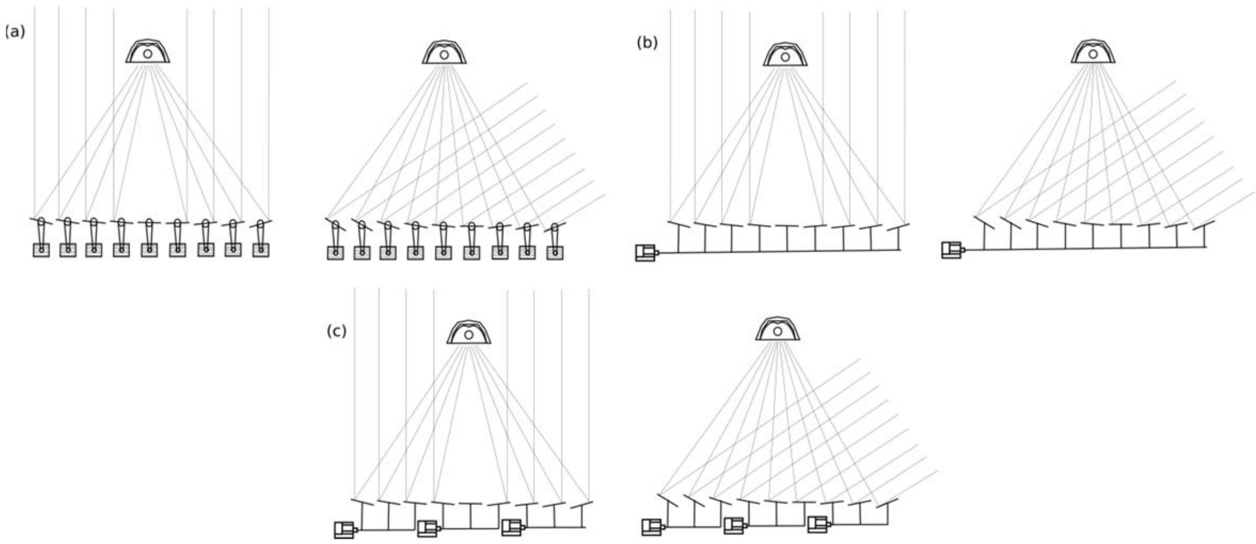

Figure 5 Sketch of tracking systems. a: Each mirror is coupled to one actuator, allowing total control over each row. b: All mirrors coupled to one actuator. c: groups of mirrors connected to one actuator

3. Qualitative design considerations in the South African context

The specification for the mirror size is due to the manufacturer's production capability (PFG Building Glass in SA). They are a manufacturer of low iron glass, however this glass cannot be used for the Fresnel as it is patterned glass. The float glass in South Africa has an iron content of 0.75% and is produced with thickness 1.8 -12 mm. It should be used as clear variaty, not green glass. The production capability has an influence on the LFC dimensions: As the stock size is a multiple of 610 mm we take that measure as the basis for our design. The mirrors produced could be 610 mm wide and 3210mm long with a thickness of 3mm. A standard mirror of 2440mm x 3210mm can be cut in 4 equal strips. The mirror curvature radius is constrained by the mirror size and thickness, but the 3mm glass should allow enough curvature.

In order to ensure a low-cost design, which maximizes the input of South African industries, basic components and materials are favored. As a first point of departure, the mirror support structure is considered. In order to ensure rigidity (little torsion and bending of construction), the structure's material mass should be minimized and the cross sectional moment of inertia in the bend plane simultaneously maximized. For these reasons standard tubing, which is available in the hosting country, is considered. However, to further reduce the structure's complexity as well as the components required to mate the mirror to the frame, square and rectangular tubing should also be selected for investigation. A further reason for selecting square tubing is that it is locally produced and easy to work with. This ensures that manufacturing time for the LFC is reduced due to the decreased complexity of the components.

The primary goal of the mirror support structure is to provide a surface for the mirror to mate to a platform for an actuator to provide the necessary movement for solar tracking. The mirror support structure will be rotated as the LFC tracks the sun throughout the day. It is critical that the mirror maintains its shape to ensure accurate reflection. Therefore, square tubing with support ribs in the zy-plane is used, which increases the material in the mirror bend plane (zy plane) but improves the rigidity and still ensuring a lightweight design.
In order to optimize the rigidity and minimize the weight of the mirror support structure a detailed Finite Element Method analysis should be conducted. This will provide insight into where the frame lacks rigidity. This could also help to reduce the amount material, which will lead to savings in weight and cost.

Drive systems have to be investigated, which are able to follow the requirements and have no backlash for performance reasons. For this reason the coupling of the motor to the mirror frame needs to be looked into detail to prevent oscillation of the reflected light on the receiver.

A control device should have an active control strategy to reduce the tracking error throughout the day will increase the performance of the LFR. An additional sun sensor could be used.

4. Collector characterization

The energy performance of line-concentrating collectors is described by the thermal balance between heat absorbed and heat lost

$$\dot{Q}_u = \dot{Q}_{abs} - \dot{Q}_{loss} \tag{1}$$

The empirical expression for calculating the useful heat approximately within a specified temperature intervall is the following

$$\dot{Q}_u = \eta_{opt,0} \cdot IAM(\theta_z, \gamma) \cdot \dot{Q}_{DNI} \cdot A_{ref} - (c_0 \times \Delta T + c_1 \times \Delta T^4) \cdot A_{Abs} \tag{2}$$

where

- $\dot{Q}_u$ is the rate of heat effectively transferred to the fluid. (W)
- $\dot{Q}_{abs}$ is the rate of heat absorbed by the absorber. (W)
- $\dot{Q}_{loss}$ is the rate of heat lost by the absorber tube. (W)
- $\eta_{opt,0}$ is the optical efficiency at normal incidence angle. (-)
- $IAM(\theta_z, \gamma)$ is the Incidence Angle Modifier at a given zenithal (θ_z) and azimuthal (γ) angle. (-)
- $\dot{Q}_{DNI}$ is the Direct Normal Incidence radiation from the sun. (W/m^2)
- A_{ref} is the reference area reflecting the DNI radiation onto the receiver. (m^2) (the reference can be chosen as e.g. the mirror area)
- c_0 is the linear heat loss coefficient. (W/mK)
- ΔT is the temperature difference between the fluid and the ambient. (K)
- c_1 is the biquadratic heat loss coefficient. (W/m^2K^4)
- A_{Abs} is the area of the absorber. (m^2)

This equation is approximate because it is not using a physical model of the different optical and thermal processes. The advantage is that for testing the empirical parameters can be fitted to experimental results. Thus the model can be used for representing collectors in a specified intervall (given by the testing) very precisely.
The first part of the right hand side in equation (2) represents the optical gains absorbed on the absorber tube surface. This is the energy available to be transmitted to the thermal fluid. The second part of the equation represents the heat losses, and describes the absorbed energy not transmitted to the fluid, as there are thermal losses from the absorber to the surroundings.
With this equation collectors can be described in annual performance calculations or simulations. It is therefore important to estimate how design changesaffect the main parameters, which are the optical losses (optical efficiency and incidence angle modifier) and thermal losses (described by the two loss coefficients). Some quantitative estimations therefore have been produced and will be presented in the next chapter.

5. Quantitiative calculations

5.1. Heat loss of single tube receiver cavity

In the following quantitative calculations were performed to get an impression, how design considerations can affect optical and thermal performance. The calculations were made using simplified design tools for the optical performance and for the thermal loss of the receiver under different operation conditions. Then the thermal performance of the collector for a complete year in South African climate (4 diffrerent locations) were investigated.

Table 3: Locations in South Africa with yearly average of ambient temperature and yearly DNI

Location	Latitude	Tamb [°C]	DNI [kWh/(m2a)]
Upington	-28.4	21.3	2863.3
Bloemfontein	-29.1	16.0	2606.3
Polokwane	-23.9	18.5	2301.4
Port Elizabeth	-34.0	17-4	1987.3

The thermal heat loss calculations were performed with a simplified tool, which uses a heat resistance model for the cavity receiver with a single tube absorber tube. The cavity is closed with a flat cover glass to protect the absorber tube and the secondary mirror from dust. The secondary mirror is assumed to be an ideally insulated wall i.e. adiabatic.
Radiation heat transfer is modelled with the a view factor method assuming diffuse surfaces. This might be not completely correct as the secondary mirror might also reflect partially specular the thermal radiation. Usually also with glass surfaces the diffuse assumption is reasonably good. For the radiative transfer the three surfaces absorber tube, secondary relector and glass cover are taken into account. No further discretization has been implemented for this study. In addition convective heat transfer from the absorber pipe to the glass cover has been assumed. It is modeled with a heat transfer coefficient according to a correlation of Morgan [5]. The convective heat transfer is from absorber tube to glass cover as the secondary is considered as adiabatic. When setting this heat transfer coefficient to zero we may also approximate a vacuum tube receiver. The results of the total radiative and convective heat transfer from absorber tube to the glass cover (and then to the ambient air) depend on the assumed emissivities of the absorber tube, reflector and glass cover. For the latter two an emissivity of 84% for glass was assumed. Also the temperature of absorber and glass cover influence the radiative heat transfer due to the strong non-linearity in the Stefan-Boltzmann law. The Nusselt number for the convective heat transfer depends on the temperature difference absorber- glass cover and the mean temperature which determines the conductivity of the air.
Already as early as 200X Mertins [6] tried to derive an empirical simplified correclation for radiative and convective heat transfer in a single-tube receiver and validated that with experiments on different absorber tube diameters and different absorber emissivities. However the experimental data for this validation used only absorber tube diameters between 13 and 17 cm. The standard commercial tubes nowadays have diameters from 25 mm to about 90 mm. In the following graph we compare the theory of Mertins with our simplified calculation. The comparison is very good for the experimental conditions close to those considered by Mertins. Also other geometries were calculated. All our results show that

the simplified model predicts somewhat higher heat losses than the empirical formula by Mertins. Therefore we can take that as a conservative approximation.

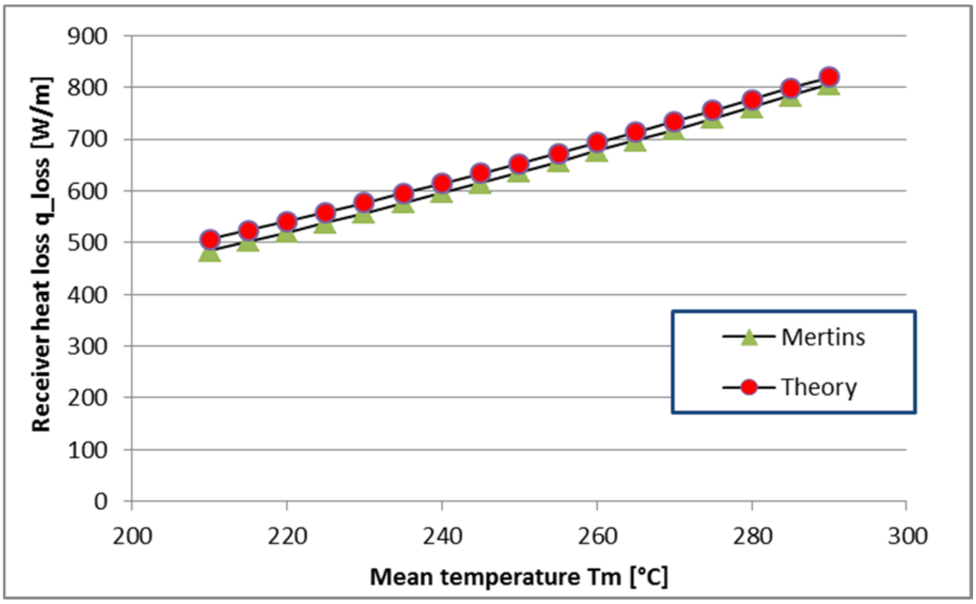

Figure 6: Comparison of receiver heat loss for temperatures Tinlet between 80°C and 240°C with an fixed outlet temperatur of Tout=380°C. The diameter of the absorber tube is 15cm, the emissivity 15%, and the aperture width / glass cover width is 62.7 cm.

5.2. Results heat loss calculations for different receiver designs

Heat loss was calculated temperature dependent with the model. Then a quadratic functions in the temperature difference between the mean of inlet and outlet temperature and the ambient temperature has been fitted to the results. In Figure 7 a receiverr with non-selective black absorber tube is considered.

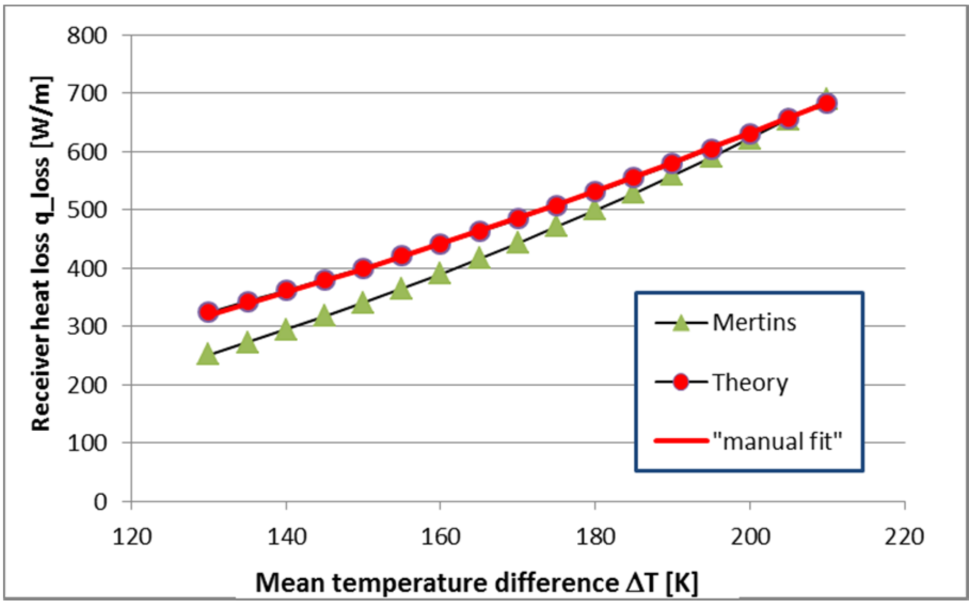

Figure 7: Temperature-dependent heat loss per meter receiver length for air-filled receiver (aperture width 0.3m, absorber diameter 70mm) for absorber emissivity 0.9. Resulting thermal loss coefficients (linear and quadratic term in ΔT) are u_0=1.16 W/mK and u_1=0.010 W/mK^2

The following Figure 8 and Figure 9 show the heat losses for selective absorbers with emissivities 20% and 10%, which gives the range for different products on the market.

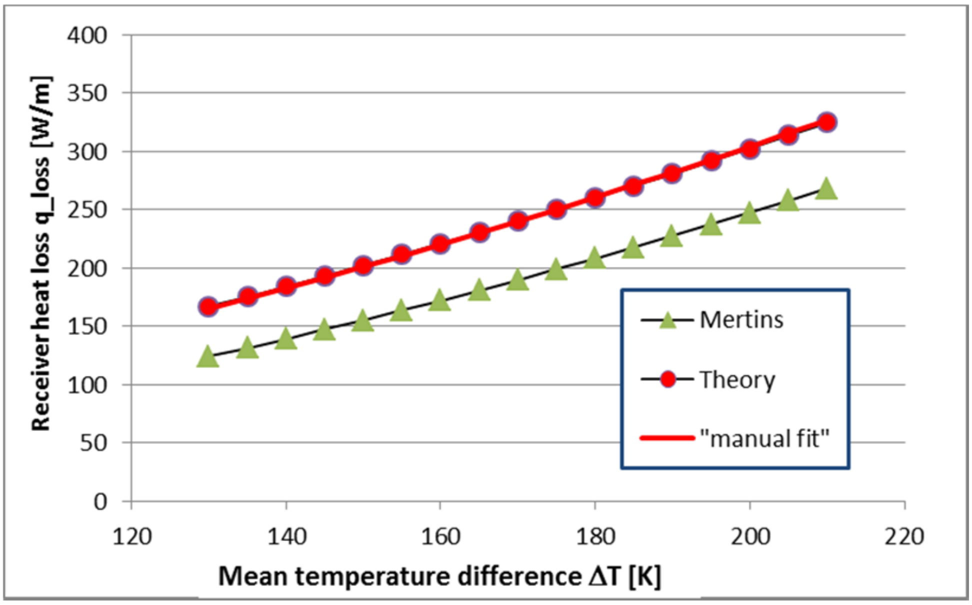

Figure 8: Temperature-dependent heat loss per meter receiver length for air-filled receiver (aperture width 0.3m, absorber diameter 70mm) for absorber emissivity 0.2. Resulting thermal loss coefficients (linear and quadratic term in ΔT) are u_0=0.80 W/mK and u_1=0.0036 W/mK^2

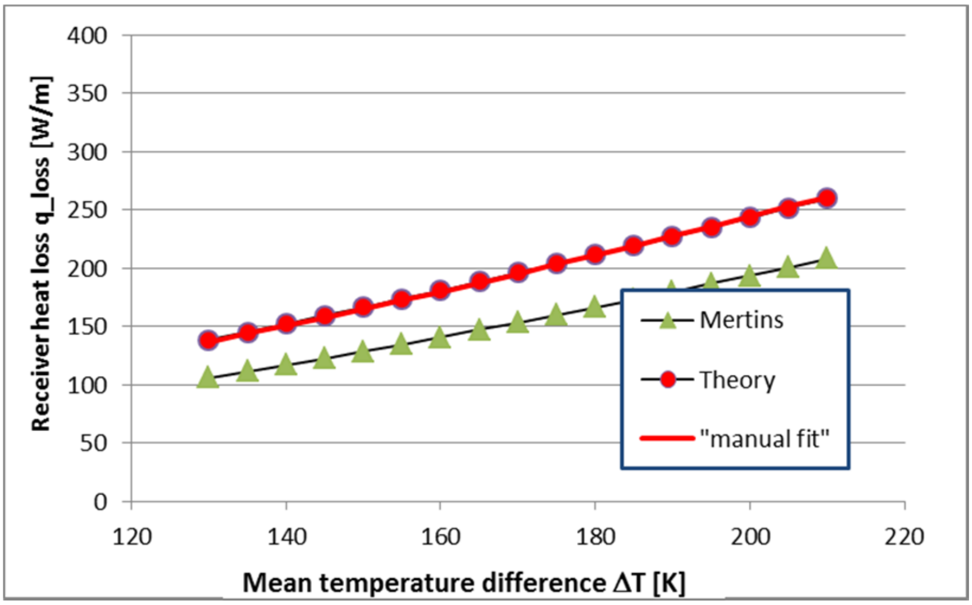

Figure 9: Temperature-dependent heat loss per meter receiver length for air-filled receiver (aperture width 0.3m, absorber diameter 70mm) for absorber emissivity 0.1. Resulting thermal loss coefficients (linear and quadratic term in ΔT) are u_0=0.74 W/mK and u_1=0.00240 W/mK^2

In order to estimate also the loss for a vacuum receiver (which is tubular) very roughly also the model of the receiver having a glass cover plate has been used with zero conductive-convective losses – as there is no coduction in the cavity the dimension of the cavity do not really matter much.

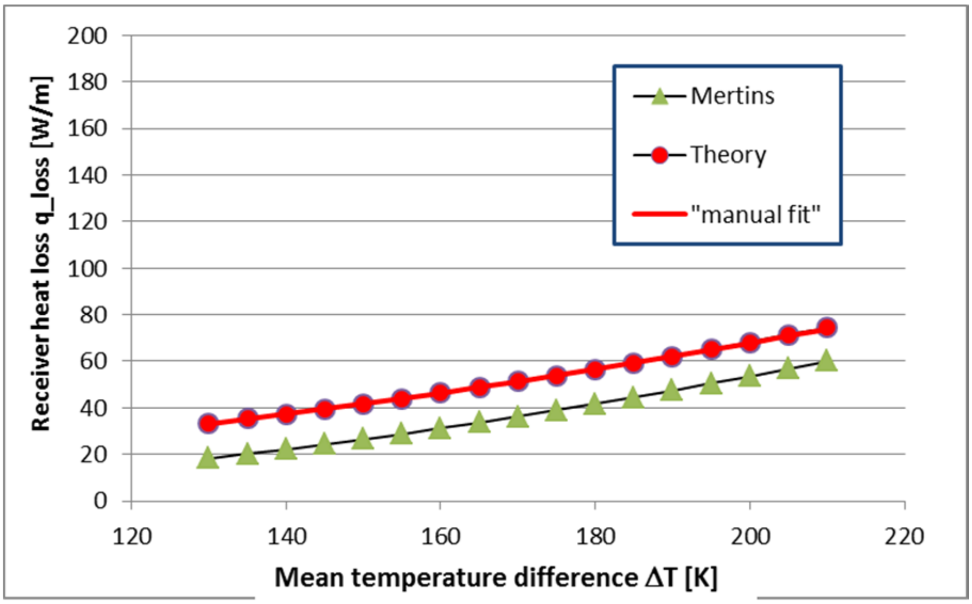

Figure 10: Temperature-dependent heat loss per meter receiver length for evacuated receiver (aperture width 0.3m, absorber diameter 70mm) for absorber emissivity 0.1. Resulting thermal loss coefficients (linear and quadratic term in ΔT) are u_0=0.095 W/mK and u_1=0.00122 W/mK^2

5.3. Optical efficiency of LFC

The optical model for the mirrorfield of N mirrors with width w and gap between the mirrors b is no raytracing model but only calculates for different incident angles the geometrical relations between mirrors, receiver aperture at height H and incoming solar radiation. Thus cosine losses, blocking losses and shading losses are considered in the model. A possible optical loss due to surface inhomogeneities, shape imperfections and non-optimized focus of the primary mirrors is only considered in a general itercept factor f_{IC}. This factor can be varied but is constant for all mirrors in a simulation.

5.4. Cases considered

In the case studies two distinguished cases were considered and simulated over a year using different meteo data.

Table 4_ Cases simulated in the design study

Case	T_{out} [°C]	T_{in} [°C]
A) Hot water temperature lifting	90	70
B) Direct steam production	210	80

The locations considered within South Africa show a wide variation of DNI, and range from Upington in the dry desert area in the Northwestern Cape region to Port Elizabeth, a maritime location in the South-West with considerably lower DNI, but still sufficient to consider concentrating collectors. Whereas the resource is optimal for Upington, the location of Port Elizabeth being more industrial is probably best with respect to the demand. The idea behind this selection is that for lower DNI a concentrating collector with different specifications and design might be the optimal solution, thus opening the possibilities for a larger market.

Table 5: Selected locations with characteristic meteorological values and latitude

Location simulated	DNI [kWh/m2a]	Ta [°C]	Lat [deg]
A) Upington	2863	21.3	-28.4
B) Bloemfontein	2606	16.0	-29.1
C) Polokwane	2301	18.5	-23.9
D) Port Elizabeth	1987	17.4	-34.0

5.5. Results of the collector calculations – Case Steam production

The simplified simulation is characterizing the collector at each hour in the year, in a quasi-static calculation for each hour of the year. Thus also idealized daily profiles for optical and thermal performance are generated. In reality considering warm-up times and dead times the exact hourly profile might look differently, however it is considered that for the annual average performance in comparison of different design options this precision is sufficient. In comparing different design options only relative ranking of options is important. Figure 11 shows an example for the hourly results for one day in the year, when the collector is oriented exactly in North-South orientation which is always taken for granted in the desgn simulations.

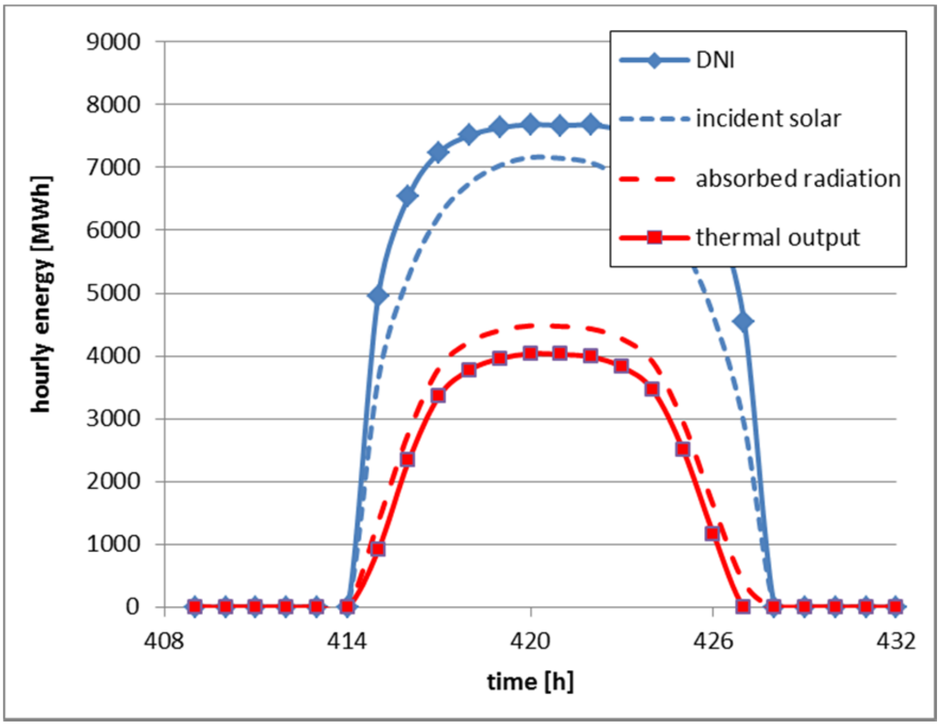

Figure 11: Example of daily energy flows in LFC

The result shows the symmetric profile on a clear summer day. Looking into the details on may also recognize the lower optical efficiency in the morning and evening hours (mainly due to cosine losses). As a selective absorber tube is assumed in the receiver (no vacuum receiver, but air-filled) the thermal losses are relatively small.

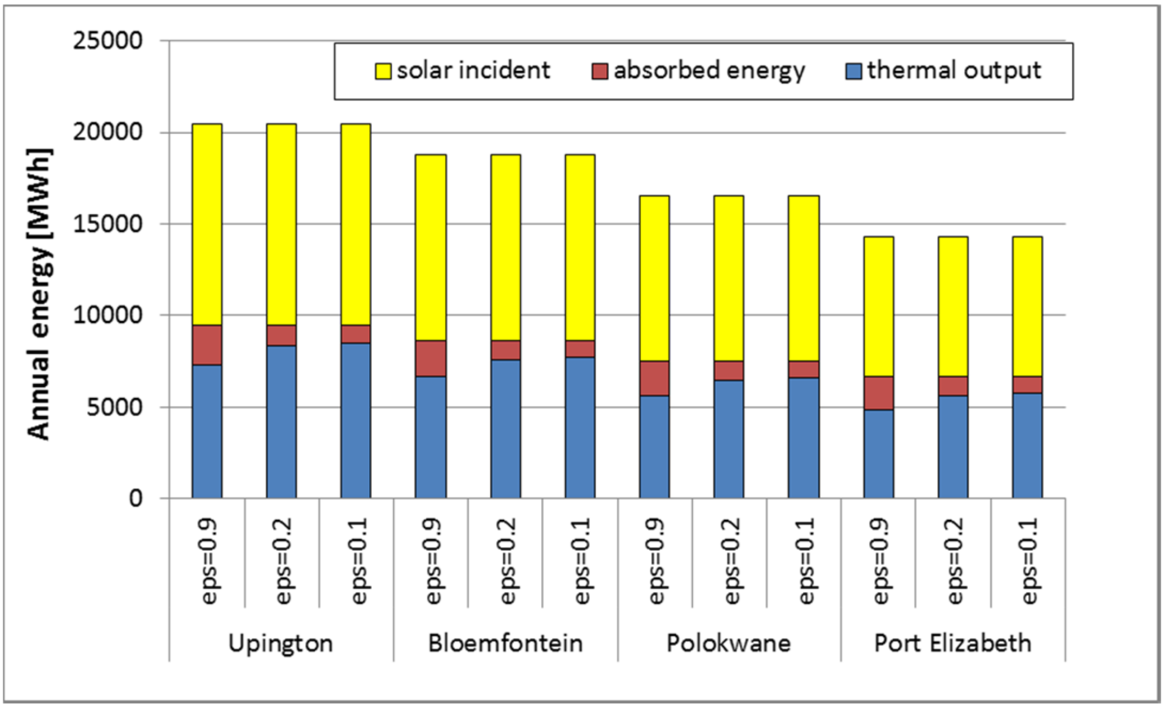

Figure 12: Annual solar incident beam radiation DNI , absorbed energy and thermal output for LFC 7200 m2, different locations, Case 1 steam production 250°C with inlet temperature 80°C
Collector parameters: receiver height H=6m, number of mirrors N=12, width w=0.6, period 0.8m

In Figure 12 the annual results of several design options are plotted for the Case 1 of steam production. Here a total mirror surface area of 7.2m2 per m collector length (12 mirrors) is considered. The emissivity of the absorber tube in the air-filled receiver is varied. The difference between selective and non-selective absorbers is relatively small though visible. Considerably larger losses are of optical nature: due to cosine losses, shading and blocking the absorbed energy is much smaller than the DNI multiplied by the mirror area. Please note that this value calculated for a parabolic trough would be a value of DNI multiplied by mirror area – not by the smaller aperture area!

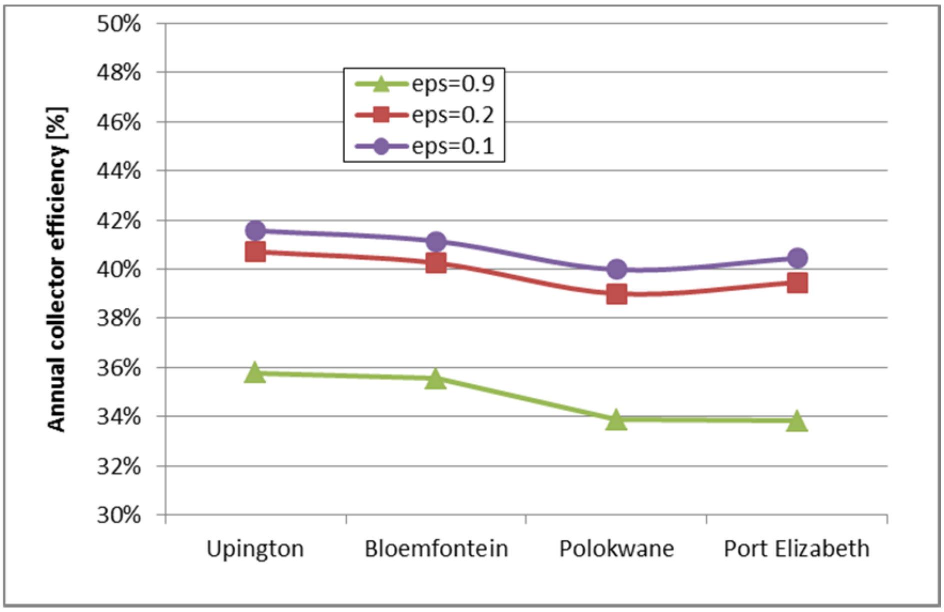

Figure 13: Annual a verage collector efficiency / utilization factor for different absorber emissivities and locations, LFC 1000 m2, Case 1 steam production 250°C with inlet temperature 80°C
Collector parameters: receiver height H=6m, number of mirrors N=12, width w=0.6, period 0.8m

Figure 13 shows that due to the higher DNI in Upington and Bloemfontein (and thus longer operation times) the annual utilization is higher in these locations. For the steam application due to the high temperatures in the collector there is a clear difference between selective absorbers and black absorbers in the receiver cavity, as thermal losses are very different. Nevertheless the efficiency values are not bad for a possible low-cost solution using just a black absorber. In order to improve the optical concentration a variation of mirror rows was considered.

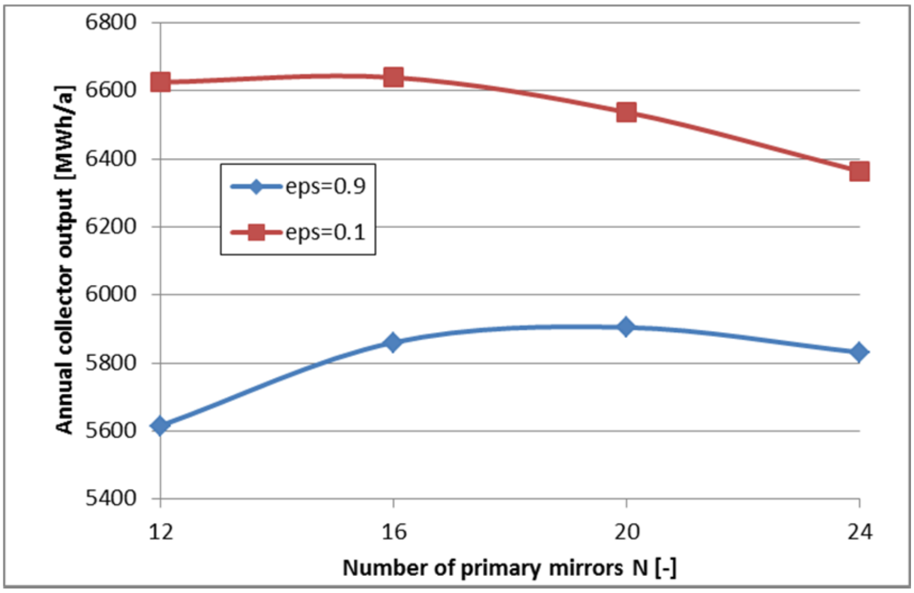

Figure 14: Optimization of number of mirrors for location Polokwane for selective absorber emissivity 10% (red) and non-selective absorber emissivity 90% (blue)
Case 1 steam production 250°C with inlet temperature 80°C
Collector parameters: receiver height H=6m, width w=0.6, period 0.8m

Figure 14 shows that collectors with selective absorbers need less mirrors as thermal losses are insignificant. For collectors with black absorbers more mirrors and thus higher optical concentration is needed to compensate for the thermal losses. An economic optimizatiion thus has to take into account the cost of more mirrors versus the higher cost of a selective absorber. The result is very similar in other locations.

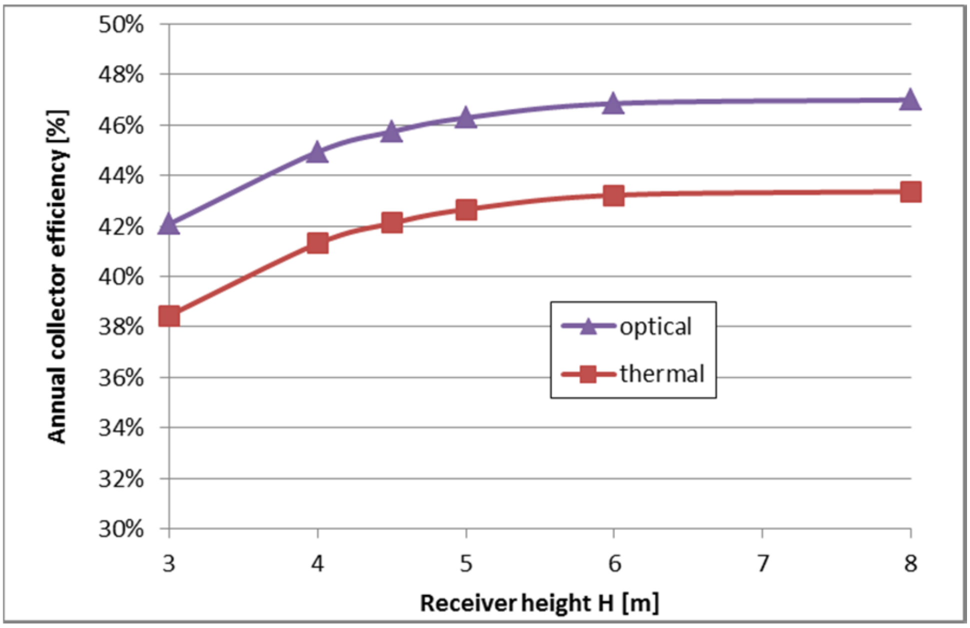

Figure 15: Annula average collector efficiency or utilization with variation of receiver height for location Upington and for selective absorber emissivity 10%
Case 1 steam production 250°C with inlet temperature 80°C
Collector parameters: receiver number of mirrors N=16, width w=0.6, period 0.8m

When more mirror rows are added to increase the optical concentration the shading and blocking losses for a fixed receiver height increase more and more. Thus for larger collector width a higher receiver could be interesting to improve the view angles. However this means also larger distance between mirror and receiver. Only if the precision of the mirrors is good enough so that the intercept of the reflected solar readiation with the receiver aperture is still very large this makes sense. For the range of heights considered we have not varied the intercept factor. This is an asssumptions which has to be checked with raytracing in detail, when a real collector design with real mirror substructures are considered.

When we take the optimum number of mirrors N=16 as derived from Figure 14Figure 15 we can see in Figure 15 that a height H=6m seems to be very good for this case and application. Higher receiver reduce the blocking and shading of mirrors, therefore with the assumption of constant optical intercept even for larger distances results in theoretically in a better optical efficiency. However that could need better quality mirrors (less shape deviations) and the gains may be negligible for larger heights than H=6m. Thus it is suggested to use H=6m.

5.6. Results of the collector calculations – Case Hot water production

When we look into the second Case2 with lower temperature hot water preheating from 70°C to 90°C, then the thermal losses are generally smaller, and therefor the question of absorber emissivity is less important. This can be seen in the comparison of different emissivity options for the absorber for the four locations considered (Figure 16).

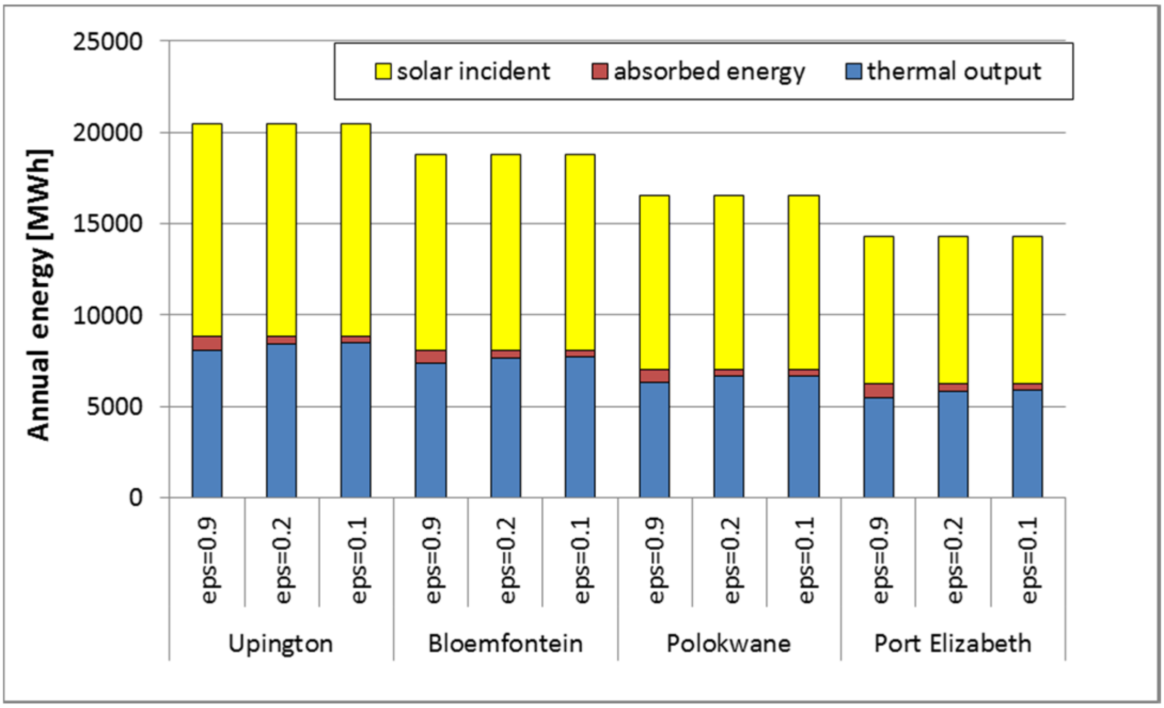

Figure 16: Annual solar incident beam radiation , absorbed energy and thermal output for LFC 7200 m2, different locations, Case 2 hot water production 90°C with inlet temperature 70°C
Collector parameters: receiver height H=4m, number of mirrors N=16, width w=0.6, period 0.8m

When compared to the Case 1 the annual collector utilization rate (averaged efficiency) is similar in shape, however the difference between selective and black absorber tubes is much smaller (Figure 17).
Please observe that due to the results of Figure 14 a number of 16 mirrors and a receiver height of 4 m has been chosen for the comparison. Certainly a larger receiver height would improve the result, however only 4m is used in this case as we assume that the collector will be rather small, possibly roof-mounted for this hot water application. It is a typical application in the use of solar heat for industrial purposes. Hence a lower receiver height is certainly easier when consideriing production, mounting and building regulations.

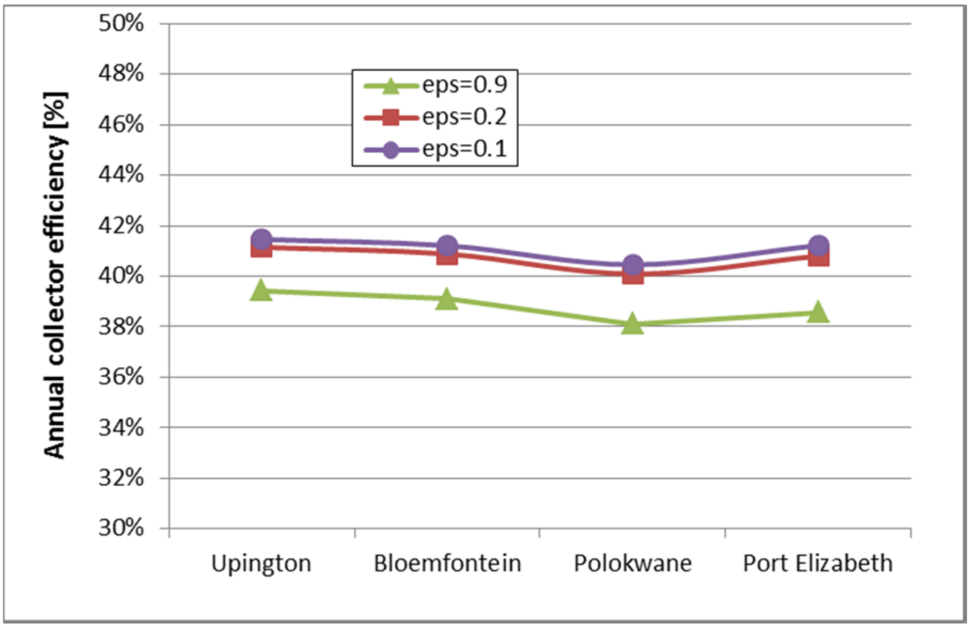

Figure 17: Annual a verage collector efficiency / utilization factor for different absorber emissivities and locations, LFC 1000 m2, Case 2 hot water production 90°C with inlet temperature 70°C
Collector parameters: receiver height H=4m, number of mirrors N=16, width w=0.6, period 0.8m

In the following Figure 18 now again the number of mirrors is optimized. And due to the lower temperature and lower thermal losses the optimal number is smaller than for the steam case (Figure 14). Two curves are shown in this graph. One is considering the case where a constant aperture for a certain collector row has been considered. Increasing the number of mirrors reduces thus collector length which leads to higher end losses (red curve). Alternatively the collector length can be kept constant but the number of collector rows (in larger fields) can be reduced (blue curve). Here the end losses are the same and only the effect of increased optical losses due to shading and blocking are considered.

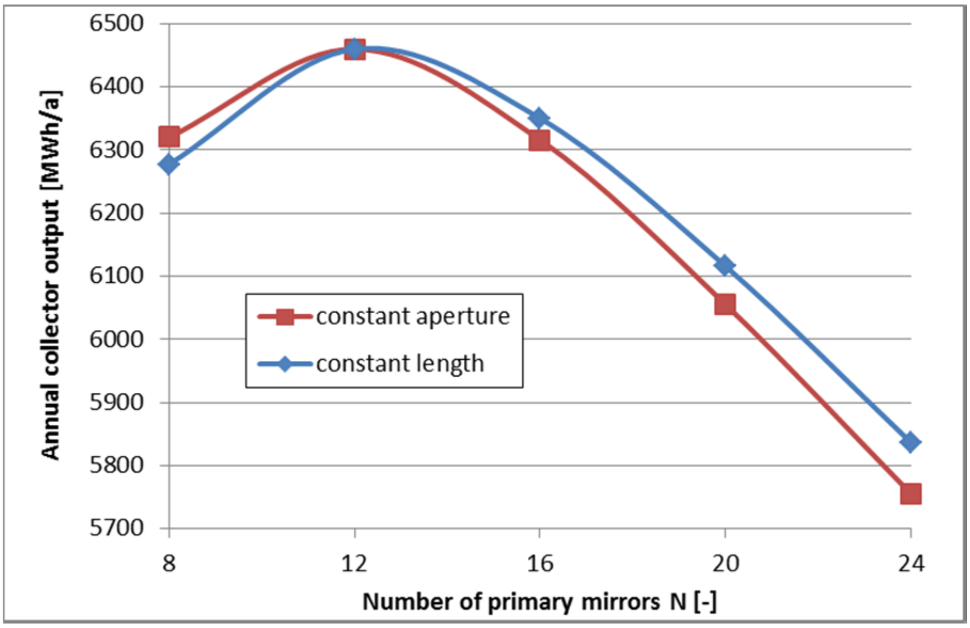

Figure 18: Optimization of number of mirrors for Case 2 low temperature hot water
Location: Polokwane, receiver height H=4m black absorber eps=0.9
a) for constant aperture and b) for constant length (same field size using less collector rows)

In the design considerations not only the geometrical variations and the receiver variations have their place, but also the selction of materials for mirrors and cover glass can be considered. The use of white solar glass is a bit more expensive, but certainly would be beneficial as well for mirrors (higher reflectance) as for the receiver cover (transittance). On the other hand in local markets only ordinary green float glass could be available. Therefore we considered also in a few simulations an exchange of materials.

Table 6: Results for simulations, location Bloemfontein, N=12, H=4m, Emissivity 0.1

Annual DNI		kWh/m2a
Annual optical efficiency		
Annual thermal efficiency		
Annual collector efficiency		
Annual solarelectrical efficiency		
Annual PB efficiency		
Annual net efficiency		
Annual solar incident	MWh	
Annual absorbed energy	MWh	
Annual thermal production	MWh	
Annual net production	MWh	
Annual gross production	MWh	

As can be seen from **Fehler! Verweisquelle konnte nicht gefunden werden.**Table 6 the change in reflectance is not so pronounced in the change of thermal output. Somewhat larger influence has the change of transmittance from white glass to ordinary green glass in the receiver cover. However if all materials are used in lower quality and also the intercept factor would be reduced, then a reduction of about 14% would be the result.

6. Discussion of low-cost concept and conclusions

Energy generated by Linear Fresnel Collectors can be transformed in electrical energy or used to feed a thermal process. For electrical generation, steam at high pressure and temperature is needed (above 250 ºC), therefore the collector is assembled with very accurate mirrors, highly transparent glass (envelope or glass plate) and an absorber with high absorptance and minimized thermal losses. These properties increase the optical efficiency of the collector. As the temperature of the absorber rises, heat loss begins to dominate. To decrease the heat loss, the absorber is coated with selective coatings to decrease the emittance and consequently the radiative heat loss. Convective heat loss depends only on the temperature difference between the absorber surface and the surrounding media, so it has been effectively suppressed by evacuating the clearance between the absorber tube and the glass envelope.

For thermal processes below 250°C on which this study is focused, the collector can be designed according to the target temperature. As the temperature level decreases, components of less quality might be used. Nonetheless, the reduction of efficiency has to be compensated by the reduction in cost. Form our results it is clear that measures changing the optical performance are much more dominant than changes in the thermal performance. We described the heat loss comparing the useful heat for different receiver configurations. On the one hand side a configuration of a single tube receiver with low emittance coating. On the other hand the second configuration has an absorber with high emittance coating (Paint) and a glass plate on the bottom.
The cost of the components depends strongly on the materials and the technology needed to manufacture it. Mass production tends to decrease the cost. Local manufacturing has a potential of decrease the costs as well. It is favourable, if products can be used which are used also in other, preferably larger, markets. Thus, the economical feasibility of local manufacturing depends on the market and on the already existing industry available in the country. If there is an industrial sector which has synergies with concentrating solar energy, the potential of reducing the cost of the component increases.

Design possibilities to decrease the cost of Linear Fresnel collectors
As alternatives to highly efficient components as used in CSP-collectors for electricity generation, we identify the following options

- White-glass (transmittance 0.91 at normal incidence) or green-glass plate (transmittance 0.87 at normal incidence) to protect the absorber, instead of a white-glass plate with anti-reflecting coating (transmittance 0.96 at normal incidence).
- Silvered green-glass reflector (reflectance 0.86) instead of silvered white-glass reflector (reflectance 0.93 - 0.94)
- Reflectors with one focal length instead of each row with optimized focal length
- Aluminum reflectors for secondary concentrator
- Non-selective black paint coated on steel tubes instead of vacuum tube receivers or selectively coated high performance steel absorbers [7]

In order to estimate whether certain design decisions should be chosen or not, exact cost information on the alternative materials and components from different sources as well as manufacturing costs have to be known. Within this general study this data are not available. It

would need a detailed commercial development, again with checking all design options with more advanced tools then used here. Only some general issues may be discussed looking at the performance data and assuming some costs.
The first question is whether non-selective absorber tubes could be used with benefit in such a low to medium temperature application. From the simulations we see that for example for the medium temperature case (Steam, 250°C) the difference of annual thermal production per unit length of the collector in Upington is nearly 1200 kWh/a. This reduced production over the nominal lifetime of the collector of 20-25 a leads to reduced savings which have to be discounted. One may calculate for certain financial parameters of a project the levelized cost of heat LCOH for both cases, high performance collector with higher investment cost, and low performance collector with lower cost. Only if the reduction of investment per unit length of receiver leads to lower LCOH this option should be chosen. For this economic analysis we just selected some typical values to show the magnitude of necessary cost reduction.

Table 7: Economic parameters for simple LCOH calculation

	Parameters	**Unit**	**Value**
1	interest rate		0.08
2	life span	year	25
3	fraction of total plant investment cost used as anuual insurance rate	m	0.01
4	fraction of total plant investment cost used as operation and maintainance		0.02
6	factor representing surcharge for EPC, project management and risk		0.2
7	cost of solar field per unit mirror area	Euro/m2	250
8	factor of plant availability		0.96

We show here some examples of comparison using our data. We assumed investment cost for the advanced high-performance collector of 250 €/m2. With this cost assumptions we calculated a LCOH, and then we determined the maximum allowable price per unit collector length for the low cost collector prducing the same LCOH:

Collector type	Annual heat [MWh]	LCOH [€/MWh]	Coll. Cost [€/m]
Advanced collector	8521	32.66	1800
Low-Cost collector	7335	32.66	1550

This means that the simple receiver tube with black paint should be 250 €/m cheaper in this case as a high-performance receiver. This is unlikely as the cost even for good vacuum receivers are in this range, so the cost savings would not be possible even if the cost of the black tube would be zero. This result holds alos for other climates. For Port Elizabeth for example the required cost reduction in order to reach the LCOH of 48.13 €/MWh in this case would be 295 €/m.

For the low temperature applications this picture might change to some extent. The same analysis shows that for the hot water production the re quired cost reduction is between 90 and 110 €/m, a value which might be possible to achieve. So in this case the design option using a black painted absorber tube should be checked in detail.

Up to now we calculated only required cost reduction if one component is exchanged, and all other design parameters would stay fixed.. However also other scenarios might exist. One might save cost for a cheaper receiver, but add some cost with an additional mirror row. These questions can be in principle be solved by optimizing the LCOH in a multi-dimensional parameter field. Also cost information on individual components (eg. In this case the addition of an addintional mirror row) has to be defined.

If we exchange a component like the mirror glass or the cover glass for the collector, similar performance reduction is observed (see Table 6). So for a exchange of highly refelcting mirrors with 91% average reflectivity to mirrors with lower reflectance a cost reduction of 15€ per m2 mirror has to be reached in order to result in the same LCOH. As the cover glass is much smaller, and the performance reduction is similar to the exchange of mirrors, here the required cost reduction for the cover glass would be nearly 290 € per m2 glass. This is certainly not reasonable. The consequence is that cheaper mirrors might be interesting, especially when in a country the mirror production for highly reflecting mirrors is not existing, and mirrors have to be imported, possibly with import tax. For the cover glass, which is a small special component however, the best option should be used, because the performance loss cannot be compensated.

As a final conclusion we have identified for low-temperature applications (< 100°C) the possibility to use a very cheap black absorber. However even under this favourable conditions the low-cost receiver has to save about 90-110 € per m in investment cost. For both, higher and low temperature applications depending on the price comparison of mirror materials with different quality, the performance loss might be acceptable for a price difference of about 15 €/m2.

7. Literature

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