Sensitivity of Energy Yield of CSP Systems with Fresnel Mirrors to Structural Parameters

Ahmet Öztürk

Advisor: Prof. Dr.-Ing. Peter Treffinger
Advisor: Zaki Iqbal

Date of Submission

Ahmet Öztürk
SS/2011
Gerberstrasse
77652, Offenburg
Germany
Abstract

Author: Ahmet Öztürk

Advisor(s): Prof. Dr.-Ing. Peter Treffinger, Zaki Iqbal

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Subject: Sensitivity of Energy Yield of CSP Systems with Fresnel Mirrors to Structural Parameters

Contents: Concentrated solar power (CSP) is a commonly researched branch of renewable energy technologies. Linear Fresnel reflector (LFR) systems are also not a very niche topic in CSP. This study aims to approach the LFR systems in a quite different concept, by considering a new way of solar tracking. In this study the Fresnel mirrors are fixed on a rotating platform which can track the sun’s azimuth angle by rotation. An analytical model to populate the mirrors on a defined area is developed and using the model a mirror setup is generated. Moreover the effects of the structural parameters on the solar yield are analyzed by using a ray tracing software. When analyzing the solar yield the study keeps focus on the optical parts of LFR systems.
Declaration of Authorship

I declare in lieu of an oath that the Master thesis submitted has been produced by me without illegal help from other persons. I state that all passages which have been taken out of publications of all means or unpublished material either whole or in part, in words or ideas, have been marked as quotations in the relevant passage. I also confirm that the quotes included show the extent of the original quotes and are marked as such. I know that a false declaration will have legal consequences.

Ahmet Öztürk

Offenburg, March 7, 2012
Foreword

I would like to thank my supervisor at the HS Offenburg, Prof. Dr.-Ing. Peter Treffinger. He offered his help, knowledge and guided me patiently during my master study. Also, I want to express my gratitude to my supervisor at CSEM-UAE research company, Mr. Zaki Iqbal, whose expertise and enthusiasm added considerably to my research experience. I appreciate his good humor, positive attitude and encouraging teaching methods.

I have to thank to all my colleagues and our CEO Hamid Kayal at CSEM-UAE, whom I am grateful for all their contributions, helps and supports. Of course I can’t forget to thank to my student friends who supported, be it their guidance or simply good laughs.

IYEM foundation and CSEM-UAE research company also deserve a big thank for their financial supports during my studies.

Special thanks goes to my mother Hacer Ozturk, my father Ismet Ozturk and my other family members who were always there for me with their supports and encouraged me to move forward in my personal and academic development wherever I am in the world. They strove and dreamed with me.

Ahmet Öztürk

Offenburg, March 7, 2012
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<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\alpha$</td>
<td>degree</td>
<td>Solar altitude angle</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>degree</td>
<td>Azimuth angle tracking error</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>degree</td>
<td>Subtended angle by the sun on the earth</td>
</tr>
<tr>
<td>$\theta$</td>
<td>degree</td>
<td>Inclination of mirrors with respect to horizontal surface</td>
</tr>
<tr>
<td>$A$</td>
<td>degree</td>
<td>Solar azimuth angle</td>
</tr>
<tr>
<td>$Ar$</td>
<td>$m^2$</td>
<td>Area</td>
</tr>
<tr>
<td>$d$</td>
<td>m</td>
<td>Diameter of the receiver tube</td>
</tr>
<tr>
<td>$E_0$</td>
<td>W/m$^2$</td>
<td>Extraterrestrial solar radiation</td>
</tr>
<tr>
<td>$E_{in}$</td>
<td>J</td>
<td>Incident solar energy</td>
</tr>
<tr>
<td>$E_{ref}$</td>
<td>J</td>
<td>Reflected solar energy</td>
</tr>
<tr>
<td>$f$</td>
<td>m</td>
<td>Focal height, height of the receiver tube</td>
</tr>
<tr>
<td>$h_r$</td>
<td>m</td>
<td>Horizontal position of the receiver tube with respect to the origin</td>
</tr>
<tr>
<td>$n$</td>
<td>-</td>
<td>Index of the mirror element on one side of the module, also the number of total mirror elements on one side of the module</td>
</tr>
<tr>
<td>$P$</td>
<td>W</td>
<td>Power</td>
</tr>
<tr>
<td>$S$</td>
<td>m</td>
<td>Shift between mirror elements</td>
</tr>
<tr>
<td>$W$</td>
<td>m</td>
<td>Width of the mirror elements</td>
</tr>
</tbody>
</table>
List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSP</td>
<td>concentrated solar power</td>
</tr>
<tr>
<td>DSG</td>
<td>direct steam generation</td>
</tr>
<tr>
<td>LFR</td>
<td>linear Fresnel reflector</td>
</tr>
<tr>
<td>MENA</td>
<td>Middle East and Northern Africa</td>
</tr>
</tbody>
</table>
1 Introduction

1.1 Motivation – Current situation

Growth in the economy and increasing living standards are welfare indicators that every country is proud of. These developments are closely bound to their energy consumption. With the world having a population and economic growth trend, as of now, we may assume that the energy consumption will increase even quicker. Increasing oil prices and global climate changes are closely affecting the supply of energy required by this inevitable growth. After the global oil crises in 1973 and 1979, the world focused on developing renewable energies. New technologies were experimented and implemented in large scales which were researched in the past, some having a history of more than two centuries. The first big scale parabolic trough, dish, solar tower and solar chimney plants were installed as a consequence of these crises. Until that time, due to market resistances, and insufficient financial and political supports of governments, the developments in this field were delayed. Due to skyrocketing oil prices and concerns of governments about security of energy supply caused rapid growth in the renewable energy market, especially in solar thermal -concentrated solar power -technologies. [1], [2]

Using concentrated solar power (CSP) systems to generate mechanical motion is not a new concept and has been researched since 1878 by its pioneers Mouchot and Pifre [3]. For the purpose of generating electricity, CSP is used in hundred kilowatts and megawatt-scale plants since the second half of the last century. Current systems used for this purpose are mostly either inefficient and cheap or efficient and costly such as solar dish or parabolic trough collectors. These projects are studied mostly for high pressure/high temperature systems with capacities in megawatt scale. [4], [5]

The most common solar thermal power concept-parabolic trough- is more costly in comparison to linear Fresnel due to the curved mirrors and tracking mechanism. Using Fresnel reflectors seems as an attractive option to solve the cost problem [6]. The classical linear Fresnel reflector (LFR) concept is cheaper in comparison to other solar thermal power technologies. But still, in LFR technology every mirror is tracking the sun autonomously to reflect the incident sunrays to the receiver which also adds to the total cost of the systems. The particular specialty of this project is to contribute in developing a low cost CSP system which will generate electricity with lower cost per kWh of electricity. This is aimed to be achieved by omitting the tracking system for each mirror and populating extra flat mirrors on a platform. The platform is capable of rotating and tracking the suns motion in azimuth angle. As a result to develop a robust, efficient, scalable, cost-effective and modular mirror design is aimed.

Utilization of fixed mirrors and choosing extra flat and small mirror strips in order to approximate to the parabolic trough a robust design is needed and small changes/errors in the structure can cause big effects on the sun rays reflected off the mirrors to the receiver.

1.2 Historical background

The sun has been a significant tool serving life to flourish on the earth since the beginning of time. Scientists and engineers utilized the solar energy for several purposes being the oldest record that at the time of ancient Greeks. Socrates’ Megaron Solar House concept suggests
building a primitive “passive solar house” by protecting the house from cold winds of north and adding more windows on the southern side of the house to utilize the sun in the winter [7]. Even if it is not likely to be true, there are statements that after two centuries of Socrates, at 212 BC Archimedes might have used solar energy to burn the attacking enemy ships by concave mirrors. [8]

Today solar energy is utilized in a variety of applications. Photovoltaic panel is a well-known technology to generate electricity. Solar thermal panels are used to provide domestic hot water, solar cooling and process heat. Putting aside directly using solar energy for thermal applications, adding some intermediate devices to the system enable us to generate electricity with thermal energy gained from the sun. Parabolic trough collectors, dish collectors, heliostat field collectors and linear Fresnel collectors are some of the wide variety of methods used to achieve high enough temperatures by solar energy which allows generating electricity since 1980s. MENA and regions near to Equatorial latitude possess a remarkable potential of solar energy to utilize. The potential is not only there for water heating or other thermal purposes but also to generate electricity. [2], [8]

1.3 Objective

The study focuses on developing a mirror setup as linear Fresnel reflector (LFR) for concentrated solar power utilization purpose. Analyzing the effect of structural errors on the solar yield\(^1\) (sensitivity analysis) of the LFR module is also an important target of this study.

The concept will be based on extra flat plate mirrors which will be fixed on a rotating platform to track the sun’s motion in azimuth direction throughout the day.

When positioning the mirror strips in the mirror setup, they should be positioned in a formation that blocking and shading of mirror strips will be minimally.

The study can be used as base for further experiments on an existing LFR module available by the CSEM-UAE research company in Ras al Khaimah, United Arab Emirates. Therefore the solar data of this region will be used in the calculations and simulations.

The existing module is also based on the principle fixed mirrors on a rotating platform yet the positioning methodology of the mirror setup and efficiency factors are unknown. Therefore this study will show how to calculate a mirror setup for LFR. Then the calculated mirror setup will be compared with the existing mirror setup using ray tracing software. For the sensitivity analysis the existing mirror setup will be used so that the results can be applied and experimented without waste of time and resource.

---

\(^1\) The solar radiation reflected by the mirrors to the receiver tube.
2 Background and Literature Review

2.1 Characteristics of the sun

Sun being the closest star to earth and placed in the center of our solar system is the main source of energy on earth. Due to the fusion reactions taking place in the sun the temperature at the core reaches 15 million K. The radiation at the surface is stated approximately to be equal to a blackbody at 5,780 K. Stefan-Boltzmann rule states that the strength of radiation leaving the surface is as following, where:

\[ M_s = \varepsilon \sigma T^4 = 6.24 \cdot 10^7 \text{W/m}^2 \]  

(2-1)

This immense energy reaches the earth in form of electromagnetic radiation in different wavelengths, solar spectrum. Due to the 149.6 million km average distance between the sun and earth the solar radiation weakens when reaching the outer limits of the atmosphere. Extraterrestrial solar radiation is stated as following:

\[ E_0 = 1353 \pm 21 \text{W/m}^2 \]  

(2-2)

The small variation is due to the small eccentricity of the earth’s orbit around the sun [5], [9].

2.1.1 Solar radiation

The solar radiation reaches outside of the atmosphere through vacuum of space. During its journey through the atmosphere to the earth surface solar radiation gets weakened because of scattering, reflection and absorption.

![Diagram of energy balance](image)

**Figure 1**: Estimate of the earth’s annual and global mean energy balance [10]

This phenomenon is illustrated clearly and comprehensively in Figure 1. The incoming solar radiation is reduced approx. to half of its initial value when reflected and absorbed by environmental factors such as clouds, atmospheric gases and aerosols. Beside that the earth radiates some amount of the energy from its surface to the sky. Again a significant amount of this radiation is returned to the earth by the greenhouse gases.
From the extraterrestrial solar radiation the remaining solar rays reaching the surface are called direct radiation or beam radiation.

Some portion of the absorbed, reflected or scattered solar radiation in the atmosphere returns to earth surface in form of short wavelength radiation. This type of radiation is called sky or diffuse radiation.

Global (total) solar radiation on the earth surface is the sum of direct and diffuse radiation. Photovoltaic panels can utilize global solar radiation where for solar thermal systems direct beam radiation is useful. [9]

2.1.2 Sun shape

The real mirrors are not capable of reflecting the sun without losses and distortion of its shape. CSP systems must use at least one mirrored surface to concentrate the incident solar energy to a receiver surface. In this case two sources of errors are affecting the sun shape. These are the surface normal deviation due to mirror shape errors and dispersion effects of non-specular surfaces. As a result reflected sun beam gets broadened. These errors can be sorted out of the results by considering a probability distribution of the errors. Since this study assumes that the mirrors used in the simulations are perfect mirrors without distortion, this effect is not considered. [11]

2.1.3 Subtended angle by the sun on the earth

Due to the large size of the sun and the finite distance between the earth and the sun, the solar rays building the solar radiation on the earth are not parallel to each other but have a slight divergence. In other words an observer on earth sees the sun with a slight geometric expansion where this expansion is stated in terms of an angle that is on average ± 0.266°. A literature survey reveals that some of the studies take this effect into consideration where others neglected. This effect will not be considered in the scope of this study. [5]

2.1.4 Limb darkening effect

Sun considered as a solar disc varies in its brightness from the center to the circumference. Because the density and at the same time the temperature of a star decreases as the distance from center increases. So the intensity of solar radiation also decreases from the center to its circumference [5]. As is the case for subtended angle by the sun on earth, this effect is taken into account in the studies of [5] and [12] but is neglected in [13] and [14]. This phenomenon is also neglected in this study since the focus lies on analyzing the effect of structural parameters.

---

2 The subtended angle by the sun on the earth varies between 0.263 and 0.272 due to the elliptic orbit of the earth around the sun.
2.2 Sun’s path

Figure 2: Sun angles allow one to determine the sun’s position for a given time

While sun and earth are moving in their determined orbits in the space, solar systems require tracking the sun where their efficiency is directly related with incidence angle of the sun rays. For tracking the sun its position in the sky with respect to a reference point on the earth should be determined accurately. The sun’s position can be defined by the following angles which are also shown in Figure 2:

- $A$ is the azimuth angle and defines the angle between the projected position of the sun on the horizontal plane and the south direction.
- $z$ is the zenith angle and is the deviation of solar position from the normal vector (up direction).
- $\alpha$ is the solar altitude angle or elevation angle. Zenith angle and solar altitude angle can be substituted for each other ($\alpha = 90 - z$). [5]

The sun angles are not only depending on the time of the day but also on the declination at the respective day of the year. To put in other words the pattern of sun’s path in the sky changes throughout the year. [15]

The sun’s height (solar altitude angle) is ranging from 0 to 90° where the azimuth is ranging from -180° to 180°. The east is defined per definition with $A = -90°$. [16]

2.3 Concentrated solar power

Solar power has relative low density which must be collected and concentrated for efficiently utilization. Solar power can be concentrated using refracting or reflecting optical surface. Reflecting optical surfaces are most commonly used method for commercial purposes so the study will focus on this side of CSP.

Reflecting concentration technologies can be grouped to four main types. These four types can be also categorized into two subcategories, depending on their focusing method, such as point focusing and line focusing. In Figure 3 a structural view of these four types is provided.

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By point focusing type of plants, the receiver -a circular area- is surrounded by reflector mirrors, all facing towards the receiver. Parabolic dish and solar tower systems are in this category. By line focusing plants, the receiver and the reflector mirrors are positioned parallel to each other. Parabolic trough and linear Fresnel systems count in this category of CSP. [16]

![CSP technologies categorized by their focusing type](image)

**2.3.1 Parabolic dish**

In this technology the mirrors are used to establish a concave shape similar to a cap cut of a sphere. The receiver lies in the focal center of the concave shape and incident sun rays are reflected to the focal point, focal area. The sun is tracked by moving the solar dish in two axes so that the mirrors are always facing the sun. Significance of this technology is to maintain a stiff and lightweight structure to make sure that receiver at the focus is kept stable. Most of the designs contain a Stirling engine directly attached to the receiver so the power generation takes place on collector as well. At some models also an additional natural gas boiler can be coupled with the system. The technology is mostly utilized for standalone systems because of their land occupation and their small sizes ranging from 10-100 kW. [2]

**2.3.2 Solar tower**

A field is covered by distributed planar mirrors, heliostats. These are capable of tracking the sun individually and reflecting to a tower having a receiver chamber at the top of it. Depending on the field size such systems can achieve a solar concentration factor of 600 to 1000. In the receiver chamber the energy is stored by a working fluid. Molten salt, air and steam are used as working fluid in various designs worldwide. The heat stored is then used to generate steam and next electricity using a conventional steam turbine. Depending on the design also a gas turbine, which takes the hot working fluid from the receiver chamber as input, can be coupled before the steam generation cycle. Due to increased efficiency of combined cycle, the required collector area can be reduced by 30 %. [17]

It is also usual that thermal storage is attached to these facilities. The 10 MW Solar II plant in California uses molten salt as working fluid and thermal storage. The Plataforma Solar in Almeria uses a wire mesh as receiver and cooled by air flowing through the mesh and for night time operations ceramic heat storage is used. [17]
2.3.3 **Parabolic trough**

In this technology parabolic shaped curved reflectors placed around one axis linear receiver are used. A long pipe is placed at the focus of the parabolic shape so that the incident nearly parallel sun rays are reflected on it. The fluid inside the pipe is heated. Depending on the design the heat is either directly used to boil water (direct steam generation) or used to heat a thermal oil. Afterwards the heat is extracted from the thermal oil using a heat exchanger. The company LUZ International installed the first parabolic trough power plant to generate electricity at 1984 in southern California. [2]

In order to collect the sun rays effectively the troughs are tilted throughout the day to track the sun’s motion. In direct steam generation (DSG) technology at some portion of the day the concentrated rays are hitting upper part of the receiver where no water but steam is accumulated. So this causes extreme heating of the pipe. Applied solutions on the market to this problem are heating a thermal fluid instead of water in the receiver or using recirculation concept. By the recirculation concept, water is first circulated in a portion of the mirror array to evaporate and then vapor is separated from liquid. Vapor is circulated in the other portion of mirror array to superheat or is superheated using a boiler.

2.3.4 **Linear Fresnel reflectors**

The word Fresnel is derived from the term Fresnel lens. The Fresnel lens, which is a stepwise lens, is invented by A. J. Fresnel (1788-1827) to prevent the increasing lens thickness by increasing diameter of the lens. The curvature radii of concentric ring zones of the lens are chosen in a way that they all have the same focal point. With this method the weight and size of the lens could be reduced significantly. [5]

Projection of the Fresnel lens concept to the mirrors is achieved by G. Francia in 1962. He designed flat rectangular mirror strips parallel to each other, populated them symmetrically on both sides of a receiver tube and made the system track the sun on one axis. This technology is currently not commercially wide spread but there are several promising researches and commercial trials in the field. Further explanation to LFR will be given in chapter 2.4. [3]

2.3.5 **Overview to the concentrated solar power technologies**

All solar thermal powe technologies possess different parameters. Considering available commercial and test plants on the market one can summarize these as following:

- Unit power capacity
- Solar concentration factor
- Annual solar efficiency
- Power generation method
- Thermal cycle efficiency
- Power specific land use

*Table 1* summarizes the main characteristics of the four most common concentrated solar power technologies. Among many others most important properties are put together with an additional comment if the technology is proven (demonstrated) or expected in the future by new researches (projected).
Table 1: Comparison of performance data for different concentrating solar power technologies [17]

<table>
<thead>
<tr>
<th></th>
<th>Capacity Unit /MW</th>
<th>Concentration factor</th>
<th>Peak solar efficiency</th>
<th>Annual solar efficiency</th>
<th>Thermal cycle efficiency</th>
<th>Capacity factor (solar)</th>
<th>Land use/m²·MWh⁻¹·y⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Fresnel</td>
<td>10-200</td>
<td>25-100</td>
<td>20 % (p)</td>
<td>9-11 % (p)</td>
<td>30-40 % ST</td>
<td>25-70 % (p)</td>
<td>6-8</td>
</tr>
<tr>
<td>Parabolic Trough</td>
<td>10-200</td>
<td>70-80</td>
<td>21 % (d)</td>
<td>10-15 % (d)</td>
<td>30-40 % ST</td>
<td>24 % (d)</td>
<td>4-6</td>
</tr>
<tr>
<td>Solar tower</td>
<td>10-150</td>
<td>300-1000</td>
<td>20 % (d)</td>
<td>8-10 % (d)</td>
<td>30-40 % ST</td>
<td>24 % (d)</td>
<td>8-12</td>
</tr>
<tr>
<td>Dish-Stirling</td>
<td>0.01-0.4</td>
<td>1000-3000</td>
<td>29 % (d)</td>
<td>16-18 % (d)</td>
<td>30–40 % Stirling</td>
<td>25 % (p)</td>
<td>8-12</td>
</tr>
</tbody>
</table>

Concentration factor = (solar reflective area) / (illuminated receiver area)
Solar efficiency = (net power generation / incident beam radiation)
Capacity factor = (solar operating hours per year / 8760 hours per year)
(d): demonstrated
(p): projected
ST: steam turbine
GT: gas turbine
CC: combined cycle

2.4 Linear Fresnel reflectors

Figure 4: Basic components of a linear Fresnel reflector module [18]

Figure 4 presents a closer look to LFR. Primary Fresnel reflector mirrors reflecting ($E_{ref}$) the incident solar rays ($E_{in}$) to the receiver tube. In some designs also a second stage reflector can be included to collect the escaping rays and redirect them back to the receiver.

2.4.1 Classical linear Fresnel reflectors (LFR)

In a classical linear Fresnel reflector design several mirror strips are populated in parallel along a receiver, which are also called primary mirrors. The primary mirrors are responsible...
to reflect the incident solar rays to the receiver which is placed at a determined height. The mirrors are populated having a certain distance between each other to reduce shadowing and blocking effects. The receiver consists of an absorber tube and optionally a secondary reflector and insulation. Secondary reflector facing with its reflective surface downwards to the primary mirrors assures to concentrate the escaping rays back on the absorber tube. Closing the secondary reflector with a glass plate from its downside prevents negative effects of dust and convection losses. [5]
To achieve reasonable solar efficiency solar tracking is a must for this system. Most common way of tracking is installation of a separate one axis tracking mechanism for every single mirror strip. Another option is moving the receiver and keeping the mirrors fixed. Although there is theoretical research done on fixed mirrors – moving receiver, commercially it is not applied [19].
This study considers extra flat fixed mirrors populated on a rotating platform which is tracking the sun in one axis, in other words tracking the azimuth angle of the sun.

2.4.2 Compact linear Fresnel reflectors (CLFR)
This concept was first developed in Australia at the University of Sydney in 1993. In contrary to a classical LFR, CLFR utilizes multiple receivers per module of mirrors, where LFR only has one receiver per module. Using multiple receivers allows a more densely populated mirror setup, and as a result, a decrease in the amount of dead space between mirror strips and an increase in the utilization of incident solar rays is achievable. Mirrors are directly aimed at the receiver and no secondary reflector is needed, which is required to be resistant to high temperatures, and high optical efficiency can be obtained. In 1999 a plant is developed having a row of mirrors 200 m long, composed of modules that are 1.6 m wide and 6 m in length. Due to a decrease in the dead space between mirrors the ratio of collected solar energy per aperture area increases. But increasing number of receivers causes more thermal losses and less solar concentration factor at receivers, although the study performed by D. Mills gives no value for it [2].
3 Mathematical Modeling of the Linear Fresnel Reflector

3.1 Physical characteristics and parameters of the selected system

The study focuses on classical LFR systems by means of mirror and receiver relation. A module is comprised of extra flat plate mirrors populated symmetrically on both sides of a receiver tube. The study diversifies from regular LFR studies by its tracking method. In a classic LFR system each mirror strip is aligned north to south or west to east and is able to track the sun independently by rotating around its longitudinal axis. In this study the mirrors will be assumed to be fixed on a rotating platform and the longitudinal axes of the mirrors will always be pointing towards the sun. The platform will be rotated from east to west during sun’s daily motion and track the sun’s azimuth angle. The allocation of mirrors on the platform is symmetric with respect to the vertical mid-plane where the receiver tube lies on.

Some assumptions are needed to be made and constraints to be determined before developing the equation model and calculating the mirror setup. The platform is able to track the sun perfectly. Incident solar rays are assumed to be coming from a planar surface source and leaving the surface parallel to each other. The receiver will be a tube with a circular cross section. Displacement of focal area through sun’s position should be considered. This means that the solar altitude angle changes throughout the day and lack of receiving solar radiation following this should be considered and solved, if possible.

Shading and blocking effects of mirror strips is a critical factor decreasing the efficiency of LFR system.

![Figure 5: Incident solar rays are not fully exploited because of shading effect][20]

It is illustrated in Figure 5 how mirrors are shaded by each other because of the too close mirror setup. A close positioning of mirrors could reduce the dead space between mirror strips and increase area utilization factor (see chapter 3.3.2) but it can also result in shading and reduce the utilization of incident solar energy. Choosing the optimum space between each mirror is the key factor to correct this error.
Figure 6: Not all of the reflected solar rays can reach the receiver because of blocking effect [20]

Figure 6 shows how reflected rays are blocked by mirror strips. For this case the receiver height plays a significant role to correct this possible error. The higher the receiver tower is, the closer can the mirrors be positioned. A drawback of using a too high receiver tower is that hitting the receiver tube by reflected sun rays becomes less accurate.

Geographical position of Ras al Khaimah - United Arab Emirates will be used to obtain the solar radiation data from the database of Metenonorm software. Only direct beam radiation will be used since diffuse radiation doesn’t affect the yield in a concentrated solar power system. Effect of atmospheric and special conditions such as clouds, long or short term precipitations, hailstorm or tsunami will not be considered. Dust, humidity and other factors affecting mirrors’ reflectance will not be considered and mirrors will be assumed to be perfect mirrors. By definition a perfect mirror has 100% reflectance (no absorption, transmittance, cosine losses etc.) and no distortion of the reflected image occurs. Therefore all wave lengths emitted by the sun are reflected homogenously. The number of mirror strips should not exceed a reasonable amount for ease of manufacturing. Surface area of module is another constraint regarding the design. Mirror design should fit within a limited area.

Parameters related with the receiver characteristic are out of the scope of the thesis. Due to this fact absorption rate, heat losses and conduction-convection properties of receiver and surrounding are not considered. To obtain the overall efficiency of a solar thermal system the efficiency of power block is also important which is not considered in this study as well.

3.2 From parabolic trough to linear Fresnel reflectors

Parabolic trough collectors are constructed based on the simple parabola theory. Vertically incident sun rays on a parabolic mirror surface are collected at the geometric focal line of the parabolic mirror system. With a sufficiently precise tracking of the sun this type of systems are capable to focus the solar power on the focal line almost all the time.

Even if there is not historical record, one can develop the idea of linear Fresnel reflectors using this phenomenon. The method starts with quite simple steps. Firstly by drawing tangents to the parabola one determines some possible points to position the flat mirrors. The mirrors’ inclination angles are equal to the slope of the tangents at those respective points.
Figure 7: Incident sun rays on the parabola are reflected to the focal point

Figure 7 shows the mirrors placed on the parabolic trough curve on a coordinate axis and the focus being on the vertical axis. Incident sun rays will be reflected towards the focal point but since the mirrors are flat, the shape of reflection will not be a line but an area. While the midpoint of the mirror aims to the focal point, the rays reflected from other two extremities of the mirror will be parallel to the middle ray (see Figure 8) and will build up a rectangular shape at the focus. The numbers on the axes of this and following figures in this subchapter are not related to units and are only given for scaling purposes.

Figure 8: Projection of the parabola on the horizontal line along vertical axis showing the reflected rays at the edges of mirrors

After placing the mirrors at tangent lines on parabolic trough, next step is to project and position the mirrors on the horizontal plane. For that purpose two methods can be applied (see Figure 9 and Figure 10). Mirrors can be projected by following either the vertical direction of incident sun rays down to the horizontal plane or following the extension of reflected sun rays to the intersection with horizontal plane.

The geometric analysis revealed that keeping the distance between two mirrors is not feasible because of the blocking and shading of the inner mirrors (see Figure 9). Moving the mirrors in vertical direction causes that the reflected sun rays no longer hit around the focal point of parabola.
The aforementioned problem doesn’t occur when moving the mirrors along the reflected sun rays towards the horizontal plane (see Figure 10) shows the case of projecting the mirrors on the horizontal line along the reflected sun rays provide to keep the mirrors at the same focus. Although the focus is kept the same the problem here is the unnecessary empty area between mirrors which results in wasting incident solar radiation.

Studying this method enables one to understand the development of Fresnel reflector concept. But the methodology is not sufficient and comprehensive enough to establish a mathematical model. So another analytic approach is introduced in the next chapter.

3.3 Mathematical modeling of the optical system of LFR

Before establishing the mathematical model, analysis of significant parameters building a LFR system is required. Following subchapters introduce these parameters and show the related equations, respectively.

3.3.1 Parameters of mirror design to be used in mathematical modeling

Figure 11 shows a simplified schematic of the mirrors and the receiver tower from the front side. Significant parameters affecting the solar yield are shown in the figure.

- $d$: diameter of the receiver tube
- $n$: index and also the number of mirror strips on each side of receiver tower in one module

Figure 9: Projection of the parabola on the horizontal line along vertical axis

Figure 10: Projection of the parabola on the horizontal line along the reflected sun ray
Sensitivity of Energy Yield of CSP Systems with Fresnel Mirrors to Structural Parameters

Ahmet Öztürk

$f$: focal height. The distance between center point of the receiver tube from the horizontal plane where bottom points of mirrors lie.

$W_n$: width of the $n^{th}$ mirror.

$\theta_n$: inclination angle of mirror measured counterclockwise from the horizontal plane.

$L_n$: distance of $n^{th}$ mirror’s bottom end from the receiver tower.

$S_n$: space between $n^{th}$ and $(n-1)^{th}$ mirrors. Measured horizontally from last point of the mirror to the first point of next mirror.

$h_r$: horizontal position of receiver with respect to the origin.

$0$: origin of the module. Mirrors’ lower ends are positioned on the horizontal line which represents the x-axis for the calculations in following chapters. The receiver tower is aligned to the positive y-axis.

\[ E_{ref} = \eta \cdot E_{in} \]  \hspace{1cm} (3-2)

Figure 11: Front view of a linear Fresnel reflector module schematic

3.3.2 Mathematical modeling of LFR (of the Optical System)

For the modeling of the optical system only direct beam irradiance of the sun is considered. The concentrator - set of mirror strips populated on the platform - is perfectly tracking the sun.

Reflected energy $E_{ref}$ by the solar collector to the focal surface is a function of the incident solar energy $E_{in}$, design, environment, and material parameters:

\[ E_{ref} = f(E_{in}, \text{design, environment, material}) \] \hspace{1cm} (3-1)

Reflected energy is basically equal to the incident energy multiplied by an efficiency factor $\eta$:
The energy initiating from the sun and reaching the receiver tube after being reflected by the mirrors is a function of incident solar energy on the mirrors, environmental effects and material properties of the mirrors. So the reflected energy is proportional to the incident energy and multiplied by an efficiency factor.

This efficiency factor $\eta$ is also a function of the design, chosen materials and environmental effects.

$$\eta = f(\text{design}, \text{material}, \text{environment}) \quad (3-3)$$

The equation for the efficiency can be expressed as the multiplication of the efficiencies for the aforementioned factors: design, material and environment.

$$\eta = \eta_{\text{design}} \cdot \eta_{\text{material}} \cdot \eta_{\text{environment}} \quad (3-4)$$

The efficiencies due to the material and environmental factors are not considered in this study. So the design efficiency can be further divided in reflector and receiver efficiencies.

$$\eta_{\text{design}} = \eta_{\text{reflector}} \cdot \eta_{\text{receiver}} \quad (3-5)$$

The efficiency of reflector $\eta_{\text{reflector}}$ is a function of its physical dimensions and design where the parameters in following equation are stated in chapter 3.3.1.

$$\eta_{\text{reflector}} = f(W, f, \theta, S, L, d) \quad (3-6)$$

Following equations are used in iteration to find a mirror design for predetermined receiver diameter, width of mirrors and height of receiver where receiver is placed on the focal line of the mirror setup.

Following five equations are based on the study of Sootha [12]. In that study the solar irradiation has been considered so that there is an angular subtense of the sun on the earth. This phenomenon was explained in chapter 2.1.3. In this study the sun rays reaching the linear reflector system has been assumed to be parallel to each other.

The equation (3-7) calculates the inclination angle of the $n^{th}$ mirror. A vertical beam is drawn downwards to the end point of a mirror and reflected off the mirror to the receiver where it hits the lower half of the receiver tangentially. $x_n$ and $y_n$ are the coordinates of this tangential point. $L_n$ is the horizontal distance of the $n^{th}$ mirror’s lower point from the symmetry plane.

$$\theta_n = \frac{1}{2} \tan^{-1}\left(\frac{L_n + x_a,n}{y_a,n}\right) \quad (3-7)$$

Using simple trigonometric equities one will obtain equations (3-8) and (3-9) which provide the required values of the tangential point on the receiver tube to calculate the inclination angle $\theta_n$ of mirror strip.

$$x_{a,n} = R \cdot \sin \theta_n \quad (3-8)$$

$$y_{a,n} = f - R \cdot \cos \theta_n \quad (3-9)$$

To prevent the blocking and shading effects of mirrors to each other a minimum space-shift should be kept between each mirror strip. Following equation calculates the required space between $n^{th}$ and $(n-1)^{th}$ mirror strips.

$$S_n = \frac{(L_{n-1} + W_{n-1} \cos \theta_{n-1} + x_{n,a})W_{n-1} \sin \theta_{n-1}}{y_{a,n} - W_{n-1} \sin \theta_{n-1}} \quad (3-10)$$
Following equation calculates where the lower end point of the mirror should be placed on horizontal plane which is required for installation. Namely this equation defines location of the respective mirror. The width of the respective mirror strip, the shift and the location of previous mirror are required parameters.

\[ L_n = L_{n-1} + W_{n-1} \cos \theta_{n-1} + S_n \]  \hspace{1cm} (3-11)

Following equations provide the factors to evaluate and compare the efficiency and functionality of the calculated mirror setup.

The concentration factor defines the ratio of collected solar energy by mirrors to the concentrated energy on the receiver.

\[ Concentration Factor = \frac{A_{mirror, effective}}{A_{receiver}} \]  \hspace{1cm} (3-12)

The gross area of mirrors define the total area used for one side of the reflector including the sum of dead space -the necessary space between each mirror to prevent blocking and shading- between mirrors and sum of mirrors’ area on the horizontal plane.

\[ A_{mirror, gross} = 2 \cdot \left[ L_1 + \sum_{n=1}^{k} W_n \cos \theta + S_n \right] \]  \hspace{1cm} (3-13)

The effective mirror area is the sum of dead space between mirrors subtracted from the gross area of mirrors.

\[ A_{mirror, effective} = 2 \cdot \sum_{n=1}^{k} W_n \cos \theta \]  \hspace{1cm} (3-14)

Area utilization factor is an important measure to determine how well the reflector area is used and how dense the mirrors are populated. A greater utilization factor allows greater reflection of incident solar energy to the receiver.

\[ Area Utilization Factor = \frac{A_{mirror, effective}}{A_{mirror, gross}} \]  \hspace{1cm} (3-15)
4 Software Modeling and Simulation

Software modeling is much like constructing a building. As any construction it also needs a plan and architecture to be based on. **Figure 12** shows a schematic of the path followed for the software modeling from the start with the definition of input parameters until end results. The check points serve as feedbacks to correct the process if any error is encountered during execution.

**Figure 12: Software architecture**

First step is to define input parameters which will be used in the equations mentioned in chapter 3.3.2. By implementing the equations and the input parameters in MATLAB code and executing, it will produce the mirror setup of LFR module.

The output -mirror setup- will be imported to ray tracing software. The software will be used to validate that the mirror setup functions correctly and reflects the incident sun rays for different solar altitude angles to the receiver tube as required. In other words this step checks the physical position of mirrors and receiver tube in 3D space. If any error is introduced so refinement of equation system or MATLAB code will be necessary.

After validation next step is to import the mirror setup to the analytical energy model (see chapter 3.3.2). Using this model one can approximate the power reflected by the mirror setup to the receiver. The result will be used to crosscheck the power results of simulation performed in ray tracing software at the next step.
At this step mirror setup will be simulated in ray tracing software to obtain the solar power yield which is the power reflected by the mirror setup to the receiver tube. The results will be compared with the results of analytical energy model. If they are matching the validation will be true and it can be continued with the next step.

The sensitivity analysis contains the significant installation parameters of a LFR module. The effect of any error on these parameters and hence on solar yield will be examined in ray tracing simulation by systematically introducing errors.

4.1 Criteria to choose solar data

For the calculation in Excel as well as the simulation with ray tracing, solar altitude angles and respective solar radiation data is required. This data is directly related with geographical position and, calendar date and time.

In order to get the widest range of solar altitude angle in Ras al Khaimah, a summer day is chosen. The height of receiver tower combined with smaller solar altitude angles result that incident rays on mirrors will be reflected far away from the receiver (see chapter 5.2). Widest solar altitude range will allow simulating this reflection behavior of mirror setup at the extremes of the range.

Figure 13 shows that the direct horizontal beam radiation values are relatively lower in summer than in spring and autumn. This is most likely due to the humidity and airborne impurities in the atmosphere.

Although the azimuth angle and solar altitude angles are greater than other seasons in summer, the peak beam radiation power during a day is lower. Still this doesn’t affect the reliability of the results obtained from the simulation. The results of solar yield analysis can easily be adjusted to different solar radiation values by dividing the solar yield with the
respective solar radiation value and multiplying with the new value (see equation (3-2)). If in a further study experiments are done, the solar yield can be updated by the respective solar radiation data at the time of experiments.

Table 2 shows the direct horizontal beam radiation, solar altitude angle and azimuth angle data at 16th June 2005 for Ras al Khaimah, United Arab Emirates. Data is taken from Meteonorm Weather database. The software provides hourly recorded data. Accordingly the solar altitude angles are not round numbers. In order to standardize the simulation results for specific positions of the sun, the solar altitude angles are rounded. The value of azimuth angle doesn’t play a significant role since during calculations and simulations the tracking platform is assumed to be perfectly tracking the azimuth angle.

Table 2: Solar data to calculate energy model at the chosen date

<table>
<thead>
<tr>
<th>Recorded time of the day</th>
<th>Direct horizontal beam radiation / Wm$^{-2}$</th>
<th>Solar altitude angle</th>
<th>Azimuth angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>06:12</td>
<td>39</td>
<td>12.3° (&lt;10°)</td>
<td>-110.1°</td>
</tr>
<tr>
<td>12:12</td>
<td>546</td>
<td>86.6° (~90°)</td>
<td>51.2°</td>
</tr>
<tr>
<td>14:12</td>
<td>488</td>
<td>60.0° (=60°)</td>
<td>92.6°</td>
</tr>
<tr>
<td>15:12</td>
<td>411</td>
<td>46.5° (~45°)</td>
<td>97.4°</td>
</tr>
<tr>
<td>16:12</td>
<td>285</td>
<td>33.2° (~30°)</td>
<td>102.1°</td>
</tr>
<tr>
<td>17:12</td>
<td>131</td>
<td>20.1° (~20°)</td>
<td>107°</td>
</tr>
<tr>
<td>18:12</td>
<td>15</td>
<td>7.4° (~0°)</td>
<td>112.2°</td>
</tr>
</tbody>
</table>

4.2 Computational model

For the calculation of mirror setup among many other options MATLAB is chosen. MATLAB is well-known and highly available software for computing with matrices. The equations mentioned in chapter 3.3.2 require to be computed in a loop. Given these conditions using MATLAB was the optimum choice.

To determine the positions of mirror elements in a linear Fresnel reflector (LFR) design, one needs to determine four main parameters.

- Width of the mirror element ($W$)
- Angle of inclination of each mirror element ($\theta$)
- Respective distance of each mirror element to a reference point ($L$)
- Space between each mirror element ($S$)

4.2.1 Calculating the mirror setup

In order to determine these parameters the equations (3-7) to (3-11) has been used. Equation (3-7) is used to calculate the inclination angle of each mirror strip and takes $x_{a,n}$ and $y_{a,n}$ as input. But then the equations (3-8) and (3-9), which calculate $x_{a,n}$ and $y_{a,n}$, take $\theta_n$ as input. To solve this problem an iteration procedure should be performed. Firstly a $\theta_n$ value is assumed and using this $x_{a,n}$ and $y_{a,n}$ are calculated. Then putting $x_{a,n}$ and $y_{a,n}$ in equation (3-7) gives another $\theta_n$ value. The $\theta_n$ values of this and previous steps are compared.
So the calculation should be put in a loop and iterated until the input $\theta_n$ to equations (3-8) and (3-9) and result $\theta'_{n}$ of equation (3-7) matches. Following this, location of mirror strip and shift between mirrors are calculated.

The code first takes input values for $d$, $f$, $W$, $\theta$, width of the LFR module on one side and minimum shift between each mirror from the user. Then initialization of variables is done. After taking inputs and initializing variables the above mentioned loop is executed. The loop calculates as many mirrors as they would fit in a somewhat wider area than the given width of the LFR module. Another small loop checks the positions of the mirrors and determines which one is the last mirror strip that fits within the defined module width.

After having the mirror setup calculated and number of mirror strips determined, next step is to round the significant figures of the results of the inclination angle, mirror locations and shift between mirrors to manufacturing limits.

In the last step the code imports the number of mirror strips, $\theta$, $L$, $S$ and $W$ to an MS Excel file. Further information regarding the operation mechanism of the code can be obtained in Appendix A from the comments in the code and the calculated mirror setup which is used in this study can be found in Appendix B.

### 4.3 Energy model

To calculate the energy reflected to the receiver tube by the mirror strips some assumptions had to be made. Since this study concentrates on the structural factors affecting the solar energy yield and the absolute values of reflected power/energy are not of particular interest, the mirrors are assumed to be perfect mirrors. It is still possible though to include an efficiency factor to calculate a realistic optical efficiency in further studies.

As explained in previous chapters, the solar data of Ras al Khaimah is used in the calculations.

A computational method was used to check the power yield results obtained by ray tracing on a reference setup as summarized above in Figure 12 and explained in the respective chapter. The calculation is crosschecked with simulation of TracePro software and since the results were correlating it was reliable to continue with the next step, sensitivity analysis to structural errors.

**Table 3: Comparison of calculated power with the simulation results**

<table>
<thead>
<tr>
<th>Solar altitude angles</th>
<th>Direct Horizontal Beam Radiation / Wm$^{-2}$</th>
<th>Energy Model Calculation / W</th>
<th>Simulation TracePro / W</th>
<th>Difference / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>546</td>
<td>24056</td>
<td>24053</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>60°</td>
<td>488</td>
<td>21501</td>
<td>21491</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>45°</td>
<td>411</td>
<td>18108</td>
<td>18091</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>30°</td>
<td>285</td>
<td>10156</td>
<td>9227</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 3 shows the comparison results. For most of the solar altitude angles in the design interval of the receiver, the calculation and simulation results match. At 30° one can observe a

---

3 This is required for ease of installation of mirror strips. Otherwise some of the first mirror strips near to the receiver tower might be too close to each other.
difference of 9%. The reason is that the receiver length is not enough to absorb all the reflected power at this solar altitude angle and the computational model was not powerful enough to consider the loss due to this factor (see Figure 15 for receiver length and solar altitude angle correlation). The energy model uses an approximation to calculate the absorbed power by the receiver. It takes the reflected sun rays from the first and the last mirror strip on one side of the module, calculates the distance the sun ray has to travel after reflection until hitting the receiver for these mirror strips. Then it takes the average of and checks where the average is hitting. If it is hitting the receiver, than that particular power is considered, if not it is recorded as missing ray.

![Figure 14: First and last mirror reflecting the incident rays to the receiver](image)

Figure 14 provides a simplified view to this concept. As one will notice that the distance \( t_n \) from the outermost mirror to the receiver tube is longer than the distance \( t_l \) from the innermost mirror to the receiver. Due to this fact for lower solar altitude angles (e.g. 30° or 45°), the outer mirrors require a longer receiver tube than the inner mirrors in order to utilize all the reflected solar energy.

### 4.4 Simulation using ray tracing

The ray tracing simulations presented in this thesis have been performed using TracePro 7.0, a commercial ray tracing simulation software. A big advantage of using this commercial software in comparison to computational ray tracing programs is it is easier and faster to simulate the solar yield of a system. This software is well tested and known where the results will be reliable. To establish a similar trustworthy program on a computational basis would be very time consuming and would not be in the main scope of this thesis. Commercial ray tracing software enables to change and modify the parameters of interest easily and the 3D geometry of the module can be simulated in this environment similar to any CAD software. This particular software’s compatibility with other CAD tools is also an advantage. Because in future when it comes to manufacture the system, further analysis can be easily conducted...
before manufacturing. The last but not the least advantage is that the software enables to write
code packages for building the geometry and assigning the values to parameters of interest.
So when building the simulation environment for different cases one may save a lot of time
which was another big constraint for this study.

The ray tracing simulations in this study are performed in three steps and to achieve three
objectives:
1. At the initial phase to validate the calculated mirror setup
2. To compare the existing mirror with the calculated mirror setup
3. To perform a sensitivity analysis on the existing mirror setup to structural errors

The results of these three steps can be seen in chapter 5.

To implement the theoretical calculated mirror setup in the simulation environment some
assumptions had to be made. Four cases of solar altitude angles were chosen as point of
interest such as:
- 90 degrees
- 60 degrees
- 45 degrees
- 30 degrees

Simulation environment is built up using three types of building blocks:
- A surface source representing sun
- Mirror strips
- Receiver tube

Any building block imported in TracePro undergoes following procedure:
1. Geometry of the block is defined (rectangular prism, cylinder, surface, etc.)
2. Dimensions of the block are defined
3. Position of the block in relation to a reference point is given
4. Surface properties of the block are defined (reflective, absorptive, etc.). For ray (light)
   emitting surfaces, emission properties are defined

In order to position these objects in the simulation environment their coordinates with respect
to a reference point in 3D space should be given. For this purpose the mirror setup data
obtained from MATLAB model (for the calculated setup) and obtained from CSEM-UAE (for
the existing setup) are exported to an Excel sheet and rearranged to match this requirement.
The accuracy for the linear measurements used in the simulation is 0.001 m and for angular
measurements 0.01°. Although the software is capable to compute with further significant
figures these limits are chosen because of the limits of manufacturing processes.

By importing of the position data from Excel sheet into TracePro the Scheme programming
language, which is a built in language in TracePro has been used. In order to save time during
implementation of repeating objects like n-mirror strips, the code is developed once and
applied iteratively for all repeating elements.

TracePro software provides a detailed material catalog including the ones available on the
market. Also theoretical material types can be chosen, e.g. perfect mirror. For the simulations
in this study the mirror surfaces are defined as perfect mirror and the receiver surface as perfect absorber. Further information can be seen in Table 4.

Table 4: Material properties applied on mirrors and receiver tube

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflectance</th>
<th>Transmittance</th>
<th>Absorptivity</th>
<th>Distortion of the incident light ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfect mirror</td>
<td>100 %</td>
<td>0 %</td>
<td>0 %</td>
<td>No</td>
</tr>
<tr>
<td>Perfect absorber</td>
<td>0 %</td>
<td>0 %</td>
<td>100 %</td>
<td>No</td>
</tr>
</tbody>
</table>

The software also offers a variety of options to define for a surface source. Following properties in Table 5 are applied to the surface source that was representing the sun in the simulation:

Table 5: Surface source properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Assigned value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission type</td>
<td>Irradiance</td>
</tr>
<tr>
<td>Flux</td>
<td>(Varying for different solar altitude angles)</td>
</tr>
<tr>
<td>Units</td>
<td>Radiometric (W/m²)</td>
</tr>
<tr>
<td>Total number of rays emitted from the surface</td>
<td>500,000</td>
</tr>
<tr>
<td>Angular distribution of rays exiting the surface</td>
<td>Normal to the surface</td>
</tr>
</tbody>
</table>

After defining the building blocks and applying the properties, next step would be starting the ray tracing. Before going into details about that, it would be helpful to understand how ray tracing phenomenon is functioning.

“TracePro is a ray tracing software for optical analysis of solid models. TracePro traces rays using “Generalized Ray Tracing”. This technique allows you to launch rays into a model without making any assumptions as to the order in which objects and surfaces will be intersected. At each intersection, individual rays can be subject to absorption, reflection, refraction, diffraction and scatter. As the rays propagate along different paths throughout the solid model, TracePro keeps track of the optical flux associated with each ray. TracePro fully accounts for the absorption, specular reflection and refraction, diffraction, and the scattering of light.” [21]

One can notice that the individual rays’ paths are simulated separately by the software which causes a processing and memory load. Based on the experiences of developers’ of the software, the number of rays is chosen as 500,000 where increasing the number have caused longer processing time and sometimes stack overflow in the memory. For this reason some of the simulations are performed using one side of the LFR module where the module is symmetric with respect to the middle plane. To obtain the solar yield of a full module with two sides the results are just multiplied with two. At some cases in the sensitivity analysis where the symmetry has been disrupted intentionally (such as horizontally displacing the receiver) both sides of the module are used.

Further details regarding figures of ray tracing can be seen in Appendix C.
5 Analysis of the Results

5.1 Comparison of existing module with the calculated module

General properties and structural specifications of the existing module and the calculated module are compared in Table 6 in a summarized way. The aperture dimensions were taken as constraints to be applied in the simulations, namely they build the physical boundaries. Receiver length is a design point which was decided collaboratively and the details are discussed further in chapter 5.2.

Table 6: Comparison of the existing module compared with the calculated module 1 – General properties

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Existing module</th>
<th>Calculated module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture width</td>
<td>3.77 m*</td>
<td>3.77 m (input)</td>
</tr>
<tr>
<td>Aperture (mirror) length</td>
<td>7.72 m*</td>
<td>7.72 m (input)</td>
</tr>
<tr>
<td>Receiver length</td>
<td>13.5 m</td>
<td>13.5 m (input)</td>
</tr>
<tr>
<td>Height of receiver</td>
<td>4 m*</td>
<td>4 m (input)</td>
</tr>
<tr>
<td>Width of mirrors</td>
<td>Varying from inner to outer mirrors*: 53, 51, 49, 47, 45 mm</td>
<td>40 mm (design point)</td>
</tr>
<tr>
<td>Receiver diameter</td>
<td>100 mm*</td>
<td>80 mm**</td>
</tr>
<tr>
<td>Number of mirrors</td>
<td>59 on one side*</td>
<td>76 on one side**</td>
</tr>
<tr>
<td>Solar reflective area (effective mirror area)</td>
<td>44.1 m²**</td>
<td>45.6 m²**</td>
</tr>
<tr>
<td>Solar concentration factor</td>
<td>79**</td>
<td>81**</td>
</tr>
<tr>
<td>$\text{Area}<em>{\text{mirror}}/$ $\text{Area}</em>{\text{aperture}}$</td>
<td>76 %**</td>
<td>78 %**</td>
</tr>
<tr>
<td>Inclination angles of first and last mirrors</td>
<td>2.81° - 21.64°**</td>
<td>2.71° - 21.57°**</td>
</tr>
</tbody>
</table>

* Data provided by CSEM-UAE
** Result of calculation and simulations

As one may notice, the existing module consists of mirrors with varying width. The reason is that the cross section of reflected sun rays off the mirrors is getting wider for the outer mirrors. Because of this, the receive width can be maintained by even a smaller mirror width and theoretically this enables one to populate more mirrors in a limited aperture width and increase the area utilization factor. In the calculated module the mirror width is kept constant. The reasons are:

1. The equation set to calculate mirror setup is based on this assumption
2. Keeping the mirror width constant decreases the effect of installation and assembly errors for outer mirrors and keeps them reflecting towards the receiver

---

* When moving from the receiver tower towards sides.
3. The resulting disadvantage in area utilization factor in a limited aperture area is compensated by decreasing the width of mirrors to 40 mm and thus decreasing the dead space between mirrors.

Solar concentration factor is one of the efficiency factors to determine to qualify a CSP system (see Table 1 and equation (3-11)). Higher concentration factors enable to reach higher temperatures at receivers and indicate better usage of solar reflective area. This performance can also be seen by the ratio of effective mirror area and the gross area of the aperture which is higher for the calculated module.

The inclination angles of the mirrors are from the important design parameters to specify the characteristics of a solar module. The effect can be observed and analyzed by the results of a simulation of solar yield.

Table 7 shows the comparison results of the calculated module with the existing module. For the comparison both modules are simulated in TracePro for different solar altitude angles and respective direct horizontal beam radiation. As expected the ratios of power difference and area difference are the same since they are linearly related to each other. Due to somewhat densely populated mirrors in the calculated module, the received power is by 3% higher than the existing module. The significant importance of this comparison is that both modules are functioning in a similar pattern and can be substituted for each other. Based on these results and due to the reasons mentioned earlier, for the sensitivity analysis the existing module will be used.

Table 7: Comparison of the calculated module with the existing module 2 – Power yield vs. solar altitude angle

<table>
<thead>
<tr>
<th></th>
<th>Direct horizontal beam radiation / Wm²</th>
<th>Calculated module P&lt;sub&gt;c&lt;/sub&gt; / W</th>
<th>Existing module P&lt;sub&gt;e&lt;/sub&gt; / W</th>
<th>Power difference ratio</th>
<th>Solar reflective area difference ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>546</td>
<td>24769</td>
<td>24053</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>60°</td>
<td>488</td>
<td>22122</td>
<td>21491</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>45°</td>
<td>411</td>
<td>18163</td>
<td>18901</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>30°</td>
<td>285</td>
<td>9513</td>
<td>9227</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>20°</td>
<td>131</td>
<td>964</td>
<td>939</td>
<td>3%</td>
<td>3%</td>
</tr>
</tbody>
</table>
5.2 Relation between the length of receiver tube and solar altitude angle

Figure 15: Receiver length and horizontal beam radiation are plotted against solar altitude angle

The horizontal beam radiation data illustrated in Figure 15 is obtained by curve fitting to the existing solar data obtained from Meteonorm mentioned before. It is a representative curve for the incident beam radiation on a horizontal surface. Using trigonometric functions, relation of the solar altitude angle with length of receiver is calculated. The smaller solar altitude angle is the longer should be the receiver tube in order to capture all the reflected sun rays. One can see that after 30 degree the solar power is considerably low and the required receiver length to absorb the total energy increases dramatically. Because of these two reasons 30 degree is chosen as the lowest position of the sun to be taken in the energy calculations and simulations. Also due to same reasons, the length of the receiver tube used in the simulations is chosen as 13.5 m. Structural constraints of the module played also a role in that, which was another ongoing research topic at CSEM-UAE. For an optimum length of the receiver tube, the thermal analysis of it is needed and suggested to be considered for further studies.
5.3 Sensitivity of received power to the position change of the receiver tube

Figure 16: Chart of power vs. vertical change in position of receiver

Figure 16 shows the power change with respect to the vertical change in position of the receiver (see Figure 17). The initial design position of the receiver is taken as origin. Then simulation is performed by linearly increasing-decreasing the height of the receiver with 1cm intervals until the received power decreases at least by 30 % at one of the solar altitude angles. Same procedure is repeated with four solar altitude angles. As a result vertical change in position of receiver should be between -4 and +5 cm to prevent power loss more than 10 %.

Considering the 4 m height of the receiver tower, 4 to 5 cm position change means an error allowance of 1 % which should not be ignored and regarded during mechanical design and manufacturing process. Still, small vibrations due to external disturbances will not have a big effect on the solar yield from the mechanical point of view.

Figure 17: Illustration of vertical change in position of receiver. The effect will occur if the receiver tube would be shifted in the direction of the red arrows
Figure 18: Chart of power vs. horizontal change in position of receiver

Figure 18 shows the power change with respect to the horizontal change in position of the receiver (see Figure 19). Since the mirror setup is symmetric with respect to the receiver tower, the change in position is considered only for one direction. The initial design position of the receiver is taken as origin. Then simulation is performed by horizontally moving the receiver to one side with 1 cm intervals until the received power at one of the solar altitude angles drops to zero. Same procedure is repeated with four solar altitude angles. As a result horizontal change in position of receiver should be less than 3 cm to prevent power loss more than 10%.

The conclusion for Figure 16 can also be deducted here that the receiver is not very sensitive to horizontal changes of position. Still the receiver is more sensitive to position changes in horizontal direction than vertical position changes. The significant drop in the solar yield is observed after 2 cm where for vertical change of position it started at 4 cm downwards and 5 cm upwards.

Figure 19: Illustration of horizontal change in position of receiver. The effect will occur if the receiver tube would be shifted in the direction of the red arrow
5.4 Sensitivity of received power to angular errors of mirrors

Figure 20: Chart of received power vs. smaller inclination angles of mirror strips

Figure 20 shows the change in received power by tilting the mirror strips in certain intervals and decreasing the inclination angle of mirror strips (see Figure 21). The initial design position of the mirror strips are taken as origin. Then simulation is performed by decreasing the inclination angle of mirror strips with 0.1° intervals until the received power drops to zero. Same procedure is repeated with four solar altitude angles. As a result tilting the mirrors for smaller inclination angle should be less than 0.1° to prevent power loss more than 10%.

A possible solution to this problem can be to install a second stage reflector above the receiver tube facing downward towards the primary mirrors. Beside that the thermal drawbacks of the second stage reflector should be analyzed since the redirected sun rays will be hitting upper part of the receiver tube. In a DSG system if the receiver tube is not filled with water and there is two phase flow in the pipe, the gaseous part of the flow will be heated. That might cause structural defects on the receiver because of local overheated areas.

Figure 21: Illustration of smaller inclination angles of mirror strips. The effect will occur if the mirrors would be tilted in the direction of the red arrows
Figure 22: Chart of received power vs. greater inclination angles of mirror strips

Figure 22 shows the change in received power by tilting the mirror strips in certain intervals and increasing the inclination angle of mirror strips (see Figure 23). The initial design positions of the mirror strips are taken as origin. Then simulation is performed by increasing the inclination angle of mirror strips with 0.1° intervals until the received power drops to zero. Same procedure is repeated with four solar altitude angles. As a result tilting the mirrors for greater inclination angle should be less than 0.2° to prevent power loss more than 10%. Within this 0.2° error the mirror is still aiming mostly at the receiver. But after that a dramatic drop is observed and the mirrors are defocussed.

The conclusion for Figure 20 can also be deducted here with an addition that the system is somewhat less sensitive for greater inclination angles. In this case the missing rays are not hitting the receiver by going away from downside of it. Making the second stage reflector longer at the edges and introducing a little bit more curvature might lessen the effect of this problem.

Making a stronger and more stable mechanical platform structure remains also as a possible solution for all of the four aforementioned error types.
5.5 Sensitivity of received power to azimuth error of tracking platform

The accuracy of azimuth tracking is a deciding factor for the cost of the system. The higher the required accuracy to track the sun, the higher will be the cost. Following results will certainly contribute in the objective of building a low cost CSP system.

Figure 24: Chart of received power vs. error of azimuth angle tracking

Figure 24 shows the change in received power when there is an error in tracking the azimuth angle of the sun. Sun being perfectly tracked was chosen as origin. Then simulation is performed by introducing an error to the azimuth angle tracking in 0.1° intervals until the received power drops to zero. Same procedure is repeated with four solar altitude angles. As a result tracking error should be less than 0.3° to prevent power loss more than 10%.

Sun tracking is a vital factor in every CSP system to obtain a high efficiency. Due to reflection geometry, the azimuth tracking error doesn’t play a role on the solar yield when the solar altitude angle is 90°. Still for lower solar altitude angles, the effect gets more powerful. The preciseness of a tracking system is most of the time directly related with its costs. This figure provides an understanding for the level of preciseness required in such a LFR system.
5.6 Summary of results

Table 8: Maximum allowable parameter change to achieve less than 1% change in the reflected power

<table>
<thead>
<tr>
<th>Affected factor</th>
<th>Error</th>
<th>Solar altitude angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>90°</td>
</tr>
<tr>
<td>Reference received power</td>
<td>-</td>
<td>24053</td>
</tr>
<tr>
<td>Mirrors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>θ smaller</td>
<td>0.1°</td>
<td>24064</td>
</tr>
<tr>
<td>θ greater</td>
<td>0.2°</td>
<td>23788</td>
</tr>
<tr>
<td>Platform</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Azimuth tracking, γ</td>
<td>0.2°</td>
<td>24053</td>
</tr>
<tr>
<td>Receiver</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal, h_i</td>
<td>± 2 cm</td>
<td>24053</td>
</tr>
<tr>
<td>Vertical, f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 4 cm</td>
<td></td>
<td>24053</td>
</tr>
<tr>
<td>+ 5 cm</td>
<td></td>
<td>24049</td>
</tr>
</tbody>
</table>

Table 8 summarizes the figures presented in this chapter. If the parameter changes are kept within the limits stated in this table the loss in received power should be less than 1%. The factors are listed in decreasing order of importance. The inclination error of the mirrors has the greatest effect on the solar yield where the allowable error interval lies between 0.1° and 0.2° for a solar power yield loss less than 1%.

To distinguish between the different types of errors and decide which one has the greater effect on the solar power yield with even a little change one should compare Table 8 and Table 9.

Most of the energy loss due to sensitivity errors takes place at the outer mirrors. Main reason for this is that their inclination angles are relatively greater than the inner mirror, which are near to the receiver and the reflected sun rays follows a shorter distance (see Figure 14). These differences make the outer mirrors more vulnerable to external disturbances. Another notable point is that azimuth tracking error is the only error type which is affected by the solar altitude angle. Azimuth tracking error is also less effective by higher solar altitude angles.

A quick look will reveal that the angular changes affect the power yield at most. Even an increase of inclination angle errors by 0.1° causes a solar yield loss of up to 33%. The azimuth angle tracking has a comparable importance as well. One can conclude that angular stability has the uttermost importance to provide a stable solar yield from a LFR module.

The changes in position of the receiver in vertical or horizontal direction are not affecting the solar yield as much as the angular errors. This indicates that the LFR module is not much affected by the environmental effects on the receiver tower such as wind and external vibrations, assuming that no angular disturbance is existent.

Most of the energy loss due to sensitivity errors takes place at the outer mirrors. Main reason is that their inclination angles are relatively greater than the inner mirrors, which are near to receiver as well as the distance between mirror and the receiver (see Figure 14). These differences make the outer mirrors more vulnerable to disturbances. Another notable point is that azimuth tracking error is the only error type which is affected by the solar altitude angle. Azimuth tracking error is less effective by higher solar altitude angles.
Table 9: Maximum allowable parameter change to achieve less than 33% change in the reflected power

<table>
<thead>
<tr>
<th>Affected factor</th>
<th>Error</th>
<th>Solar altitude angle</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>90°</td>
<td>60°</td>
<td>45°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Received power on the receiver / W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference received power</td>
<td>-</td>
<td>24053</td>
<td>21500</td>
<td>18097</td>
<td>9267</td>
</tr>
<tr>
<td>Mirrors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>θ smaller</td>
<td>0.2°</td>
<td>20818</td>
<td>18600</td>
<td>15657</td>
<td>8009</td>
</tr>
<tr>
<td>θ greater</td>
<td>0.3°</td>
<td>16093</td>
<td>14381</td>
<td>12055</td>
<td>6259</td>
</tr>
<tr>
<td>Platform</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Azimuth tracking, γ</td>
<td>0.3°</td>
<td>24053</td>
<td>21459</td>
<td>18088</td>
<td>6879</td>
</tr>
<tr>
<td>Receiver</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal, h</td>
<td>± 4 cm</td>
<td>20603</td>
<td>18418</td>
<td>15496</td>
<td>7773</td>
</tr>
<tr>
<td>Vertical, f</td>
<td>- 8 cm</td>
<td>18431</td>
<td>16457</td>
<td>13860</td>
<td>7451</td>
</tr>
<tr>
<td></td>
<td>+ 8 cm</td>
<td>20687</td>
<td>18464</td>
<td>15551</td>
<td>7927</td>
</tr>
</tbody>
</table>
6 Conclusion

Linear Fresnel reflector is a promising technology despite of its relative lower efficiency in comparison to other CSP technologies. Its low cost and easy manufacturability provides powerful advantages.

In this study, an equation model to generate a LFR mirror setup is built. Based on this equation model a LFR mirror setup is calculated and the calculated module’s functionality is validated by in ray tracing simulation. Developing a mirror setup without blocking and shading has been accomplished.

After proving that the calculated mirror setup functions correctly, the existing LFR module of the CSEM-UAE and the calculated LFR module are compared via ray tracing simulation. The similar characteristics and solar yields of the modules allowed continuing with the sensitivity analysis on the existing module. This shift from calculated to existing module was necessary in order to enable a faster start of further experiments for future researches.

Sensitivity analysis revealed that the solar yield is highly dependent on the angular accuracy of both mirror installation and azimuth tracking. The stability of receiver tower structure also has significant effects but not as crucially as angular stability. It has been also proved that the LFR system should be unaffected by small vibrations due to external disturbances such as wind, unless no angular error is introduced. In accordance to these before manufacturing the LFR module, manufacturing and installation error margins and preciseness should be considered thoroughly and measures should be taken accordingly.

For future works, before continuing with experimental research it is suggested to conduct a research on thermal behavior of the receiver tube and the fluid in it. Only then the results can be used to build a reliable experimental setup and a realistic overall efficiency for the whole LFR module can be calculated. Since research and engineering are iterative processes also in advance this study might need to be updated in light of these future results.
7 Bibliography


A. MATLAB Code

```matlab
function [InclinationAngle, Location, Shift] = base_module()
% [theta, L, S] =
% The function base_module takes the three input variables width of mirror, diameter
% of receiver and focal height of receiver from central line. The unit is in meters.
% As output the four parameters to locate the mirrors will be returned. These are:
% theta: inclination angle of mirrors
% L: location of the mirror's lower end with respect to central line
% S: Spacing between each mirror element
% n: Number of mirror elements on one side of central line
% In order to obtain reasonable significant figures, an engineering (design) decision should be taken. Regarding the available manufacturing preciseness in Ras al Khaimah, 2 digits after millimeter are chosen. (eg. 1.04mm=0.00104m). For rounding a function called roundDigit (please see bottom of the code) written by the author is used.

% Author: Ahmet Öztürk
% Sponsors: CSEM-UAE, Ras al Khaimah, United Arab Emirates; HS Offenburg, Offenburg, Germany

%% Initialization of values
m = 0;
w = 0;
d = 0;
f = 0;
moduleWidth = 4;
min_shift = 0.003;
disp('All the values should be entered in meters')

% Taking user input. If following parameters are not defined in the code, it should be taken from the user using following lines.
% w=input('Please enter a value for mirror width w=');
% d=input('Please enter a value for receiver diameter (it is suggested to assign d=w) d=');
% f=input('Please enter a value for focal height f=');
% moduleWidth=input('Please enter a value for module width on one side=');

% This segment should be deleted when user input above is enabled. From here
w = 0.04;
d = 0.04;
f = 4;
moduleWidth = 4;
% until here
firstMirrorsLocation = 0.36;

R = d/2;
zeta = 0;
n = round(moduleWidth/w);
theta = zeros(n, 1);
L = zeros(n, 1);
S = zeros(n, 1);
x_a = zeros(n, 1);`
```
% Code
S(1)=0;
L(1)=firstMirrorsLocation;

theta_dummy=0;
theta(1)=0.05;
for i=1:1:n
    if (i==1)
        counter=0;
        while (theta(i)==theta_dummy)
            theta_dummy=theta(i);
            x_a(i)=R.*sin(pi/2-2*theta(i));
            y_a(i)=f-R.*cos(pi/2-2*theta(i));
            theta(i)=0.5.*atan((L(i)+x_a(i))/y_a(i));
            counter=counter+1;
            if counter==50
                break;
            end
        end
        message=sprintf('Counter(%d) is:%d',i,counter);
        disp(message);
    else
        counter=0;
        while (theta(i)==theta_dummy)
            theta_dummy=theta(i);
            x_a(i)=R.*sin(pi/2-2*theta(i));
            y_a(i)=f-R.*cos(pi/2-2*theta(i));
            S(i)=(L(i-1)+x_a(i)+w.*cos(theta(i-1))).*w.*sin(theta(i-1))./(y_a(i)-w.*sin(theta(i-1)));
            if (S(i)<min_shift)
                S(i)=min_shift;
            end
            L(i)=L(i-1)+w.*cos(theta(i-1))+S(i);
            theta(i)=0.5.*atan((L(i)+x_a(i))/y_a(i));
            counter=counter+1;
            if counter==50
                break;
            end
        end
        message=sprintf('Counter(%d) is:%d',i,counter);
        disp(message);
    end
end

%% Total width covered by mirrors in meters
widthCovered=L(1);
for i=1:1:n
    if(widthCovered<moduleWidth)
        widthCovered=w.*cos(theta(i))+S(i)+widthCovered;
        m=i;
    elseif(widthCovered>moduleWidth)
        widthCovered=widthCovered-w.*cos(theta(i))-S(i);
        m=m-1;
        break;
    end
end

end
%% Writing the input parameters and results in Excel File
InclinationAngle=radtodeg(theta(1:m));
Location=L(1:m);
Shift=S(1:m);
m;
Width(1:m,1)=w;

inputColumnHeader={'Receiver Diameter';'Mirror Width';'Focal Height';'Module Width'}; % divided in rows
inputParameters=[d;w;f;moduleWidth];
inputUnits=['m';'m';'m';'m'];
numericalInputData=num2cell(inputParameters);
inputData=[inputColumnHeader,numericalInputData,inputUnits];
xlswrite('C:\Users\Ahmet\Documents\MATLAB\Tez\Mirrors.xlsx',inputData,'Input_Data');

columnHeader={'Id';'Inclination Angle';'Location';'Shift';'Mirror Width'}; % divided in columns
data(:,1)=1:1:m;
data(:,2)=roundDigit(InclinationAngle,2);
data(:,3)=roundDigit(Location,3);
data(:,4)=roundDigit(Shift,3);
data(:,5)=Width;

roundDigit(5.342342342,2)
numericalData=num2cell(data);
allData=[columnHeader;numericalData];
xlswrite('C:\Users\Ahmet\Documents\MATLAB\Tez\Mirrors.xlsx',allData,'Mirror_Setup');

function [roundedResult]=roundDigit(numb1,int1)
%roundDigit function rounds the 'numb1' to the nearest number towards %plus infinity with a significant figure of 'int1' after period.
%Function can round until 5 digits after period.
switch int1
    case 1
        roundedResult= ceil(numb1.*10)/10;
    case 2
        roundedResult= ceil(numb1.*100)/100;
    case 3
        roundedResult= ceil(numb1.*1000)/1000;
    case 4
        roundedResult= ceil(numb1.*10000)/10000;
    case 5
        roundedResult= ceil(numb1.*100000)/100000;
    otherwise
        roundedResult=numb1;
end
end
end
### B. Mirror Setup Data

**Table 10: Data of the calculated mirror setup**

<table>
<thead>
<tr>
<th>Mirror Index $n$</th>
<th>Inclination Angle $\theta$</th>
<th>Location $L$</th>
<th>Shift $S$</th>
<th>Mirror Width $W$ /m</th>
<th>Mirror Length $L$ /m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.72</td>
<td>0.360</td>
<td>0.000</td>
<td>0.04</td>
<td>7.72</td>
</tr>
<tr>
<td>2</td>
<td>3.02</td>
<td>0.403</td>
<td>0.003</td>
<td>0.04</td>
<td>7.72</td>
</tr>
<tr>
<td>3</td>
<td>3.33</td>
<td>0.446</td>
<td>0.003</td>
<td>0.04</td>
<td>7.72</td>
</tr>
<tr>
<td>4</td>
<td>3.63</td>
<td>0.489</td>
<td>0.003</td>
<td>0.04</td>
<td>7.72</td>
</tr>
<tr>
<td>5</td>
<td>3.93</td>
<td>0.532</td>
<td>0.003</td>
<td>0.04</td>
<td>7.72</td>
</tr>
<tr>
<td>6</td>
<td>4.23</td>
<td>0.575</td>
<td>0.003</td>
<td>0.04</td>
<td>7.72</td>
</tr>
<tr>
<td>7</td>
<td>4.53</td>
<td>0.618</td>
<td>0.003</td>
<td>0.04</td>
<td>7.72</td>
</tr>
<tr>
<td>8</td>
<td>4.83</td>
<td>0.661</td>
<td>0.003</td>
<td>0.04</td>
<td>7.72</td>
</tr>
<tr>
<td>9</td>
<td>5.13</td>
<td>0.704</td>
<td>0.003</td>
<td>0.04</td>
<td>7.72</td>
</tr>
<tr>
<td>10</td>
<td>5.43</td>
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C. Ray tracing simulation

Some example figures regarding the ray tracing environment is provided here.

Figure 25: Snapshot of the simulation environment before ray tracing

The Figure 25 shows a one sided module with sun at 45° solar altitude. The green field below is composed of mirror strips positioned parallel to each other. Above, in direction of y-axis, the receiver tube is placed. The Sun
The Figure 26 illustrates the same system in Figure 25 after ray tracing. The red lines are compiled together into a huge block as if they were solid. Zooming in the system will reveal that they are all individual rays exiting the surface and hitting the receiver. In order to have a better overview, the rays which go away due to the dead space between mirrors are not illustrated and only rays hitting the receiver are shown. The green triangle at the lower part of the figure is the part of the mirrors which cannot aim the receiver due to the lower solar altitude angle.