Advanced CSP Teaching Materials

Chapter 6
Linear Fresnel Technology

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## Nomenclature

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<th>Symbol</th>
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<th>Unit</th>
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<tbody>
<tr>
<td>( d_i )</td>
<td>distance between a mirror row and the middle axis of the collector</td>
<td>m</td>
</tr>
<tr>
<td>( f )</td>
<td>focal length</td>
<td>m</td>
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<td>( h )</td>
<td>height</td>
<td>m</td>
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### Greek letters

<table>
<thead>
<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>( \alpha_s )</td>
<td>solar altitude angle</td>
<td>°</td>
</tr>
<tr>
<td>( \alpha_T )</td>
<td>transversal solar altitude angle</td>
<td>°</td>
</tr>
<tr>
<td>( \beta_i )</td>
<td>angle between horizontal and line from mirror to absorber</td>
<td>°</td>
</tr>
<tr>
<td>( \gamma_s )</td>
<td>solar azimuth angle</td>
<td>°</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>mean mirror slope deviation (mirror quality)</td>
<td>mrad</td>
</tr>
<tr>
<td>( \varphi_i )</td>
<td>tilt angle of a mirror row</td>
<td>°</td>
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### Acronyms

- **CNRS**: French National Center for Scientific Research
- **COMPLES**: Mediterranean Cooperation for Solar Energy
- **DLR**: German Aerospace Center
- **DNI**: direct normal irradiation
- **ISE**: Fraunhofer Institute for Solar Energy
- **LCOE/LEC**: levelized cost of electricity
- **PSA**: Plataforma Solar de Almería
Summary

In this section we will get to know an alternative to parabolic trough power plants – linear Fresnel power plants. We will get to know the main components of a Fresnel power plant and we will understand the differences from parabolic trough power plants. Special emphasis will be placed on the advantages and disadvantages that the Fresnel technology has in comparison to the parabolic trough technology.

Key questions

• Which practical experiences with Fresnel technology do exist?
• Which components does a Fresnel power plant consist of?
• What are the advantages and disadvantages of the Fresnel technology over the parabolic trough technology?
There are two types of line-focusing collector systems in CSP plants: parabolic troughs and linear Fresnel collectors. Parabolic troughs represent the optimal solution concerning the achievable concentration ratio and the achievable energy yield per aperture area and, hence, the overall plant efficiency in line-focussing mirror systems. That’s why the CSP development efforts concentrated much on the parabolic trough geometry. Nevertheless, in the last decade also Fresnel collectors aroused an increasing interest. The main reason for that was the search for cheaper solar field solutions. The considerable economic advantages of Fresnel collectors are principally related to their constructive simplicity. Additionally, Fresnel solar fields permit higher land use efficiency than any other type of solar fields. If these advantages are sufficiently strong in relation to the lower solar-to-electric efficiency, than Fresnel power plants represent an interesting alternative to parabolic trough power plants.

1. The Fresnel principle

The linear Fresnel reflector technology receives its name from the Fresnel lens, which was developed by the French physicist Augustin-Jean Fresnel for lighthouses in the 18th century. The following picture shows such a lighthouse Fresnel lense.

![Fresnel lens in a lighthouse](source: www.panoramio.com)

**Figure 1:** Fresnel lens in a lighthouse (source: www.panoramio.com)

The principle of this lens is the chopping of the continuous surface of a standard lens into a set of surfaces with discontinuities between them. This allows a substantial reduction in thickness (and thus weight and volume) of the lens, at the expense of reducing the imaging quality of the lens.
The principle of dividing an optical element in segments that have together the same (or a very similar) optical effect like the original optical element can be applied also to mirrors. So, it is possible, for instance, to divide a paraboloid mirror (parabolic dish) into annular segments (forming, thus, a circular Fresnel mirror), which focus the light that arrives in rays parallel to the optical axis onto the focal point of the paraboloid mirror. In an analogous way, a linear Fresnel mirror can be constructed substituting a parabolic trough by linear segments that focus the radiation that arrives in a plane parallel to the symmetry plane of the parabolic trough onto the focal line of the parabolic trough. Concerning the concentration of the radiation in a focal line, a linear Fresnel collector has a similar effect like the corresponding parabolic trough, i.e. like a parabolic trough with the same focal length and the same aperture.

4 Of course, it does not have exactly the same effect. The optical paths of the corresponding rays after the reflection are not exactly identical and the incidence angles in the focal plane are slightly different. Additionally, linear Fresnel mirrors for CSP plants are movable so that also direct radiation that does not enter the system in a plane parallel to the optical axis plane can be concentrated.
2. History and current producers of Fresnel power plants

The first prototype of a linear Fresnel reflector concentrator was built in 1964 in Italy by the self-educated mathematician Giovanni Francia. He tested it at the Lacédémone-Marseille solar station with support from France’s National Research Council (CNRS), NATO and the Coopération Méditerranée pour l’Energie Solaire (COMPLES).\(^5\)

![Figure 4: The linear Fresnel collector of Giovanni Francia (source: Silvi)](image)

At the beginning of the new millennium, the Fresnel technology gained more influence. The first company that constructed a prototype was Solarmundo from Belgium. Solarmundo started testing a 2,500 m\(^2\) collector in Liège, Belgium, in 2001. They attracted attention with their claim to be considerably more cost effective than other existing radiation concentration systems.\(^6\)

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The presentation of the Solarmundo prototype was the signal for an ongoing stronger interest in the Fresnel technology.

In 2004, the Australian company Solar Heat and Power, which moved later to the USA and changed its name to Ausra, built a Fresnel collector in Liddell/Australia that generated steam and had a thermal power of 1 MW. From 2005 to 2008, Ausra amplified it to 9 MW. The Fresnel collector supplies thermal energy to a coal power plant. At the end of 2010 a further extension of the solar field was announced. Until 2012 the German Novatec Solar will build another Fresnel solar field, which will approximately double the solar thermal capacity of the Liddell power plant.\(^7\)

\(^7\) See Novatec Solar 2010.
In 2008, Ausra built the first Fresnel power plant (solar only) in Bakersfield/California. Its electric power reaches 5 MW. Ausra was acquired in 2010 by the French Areva group.

In Europe, the Solar Power Group (SPG), which was founded in 2004 by team members of the former Solarmundo company, participated in the construction and operation of the so-called Fresdemo pilot collector at the Plataforma Solar de Almería/Spain in 2007. The project was realized in cooperation with the DLR, MAN Ferrostaal and the Fraunhofer Institute ISE. This project made it possible to obtain many valuable investigation results.
The first commercial Fresnel power plant in Europe, PE 1, was built by Novatec Solar AG (at that time Novatec Biosol). PE 1 is situated in Murcia/Spain and has an electric power of 1.4 MW. It started commercial operation in March 2009.

A second Fresnel power plant, PE 2, is under construction. With 30 MW electric power it will be the largest Fresnel power plant worldwide at the moment when it starts its operation.
Figure 10: PE 2, which will be the largest Fresnel power plant with 30 MW electric power (source: Novatec Solar)

More Fresnel power plants are currently planned and under construction in Spain as well as in the USA.

Important Fresnel system suppliers for the electricity sector are the Novatec Solar AG in Germany, Ausra, which belongs now to the French Areva group, in Australia and the United States and the German Solar Power Group GmbH. The German Industrial Solar (former Mirroxx) GmbH concentrates on Fresnel collectors for process heat generation.
3. Plant components

In this section we will present some important Fresnel plant components. Major importance will be given to the collector.

Figure 11: Important Fresnel power plant components (source: Novatec Solar)
3.1 Collector

The mirrors in the realized linear Fresnel collectors are made of flat mirror stripes, which receive a small curvature by mechanical bending. Like in parabolic troughs, the reflecting material is silver. In the case of the Novatec Solar plants, the mirrors are glass mirrors with a glass layer of 3mm thickness.

Important parameters in the design of the primary collectors are the width of the stripes, the width of the complete collector, the number of parallel mirror stripes, the height of the absorber above the primary mirror plane, the space between the mirror stripes and the curvature of the mirrors. For all of these parameters an optimal measure has to be found:

- The width of the individual mirror stripes should not be too narrow because this would mean that for the same aperture area a very high number of mirror stripes would be needed (with a corresponding more complex space frame structure and tracking mechanism). On the other hand, they should not be too broad because this would reduce the effectiveness of the operation principle of the Fresnel mirror type. Only if the mirrors are sufficiently narrow, it is possible to reflect constantly the direct radiation onto the fixed absorber tube. At very broad mirrors the astigmatism effects (see below) are stronger.\(^8\)

Now, let’s have a look at the collector width: Very narrow collectors have the disadvantage that less aperture area is applied to one absorber tube so that less radiant flux is achieved at the absorber tube. Too broad collectors, on the other hand, present the problem that the contribution of the outer parts of the collector, which are more distant from the absorber tube, is less and much more sensible to geometrical mirror errors and tracking inaccuracy. Additionally, the very inclined incidence of the reflected radiation on the receiver at very

\(^8\) To make this more illustrative, take the extreme case of a very broad mirror, which must be similar to a parabolic trough. In this case it is obvious that it is not possible to achieve a clear cut Sun image in the focal plane at different Sun positions.
broad collectors presents problems concerning the secondary concentrator geometry and the lower transmittance of the glass pane at high incidence angles.

If we consider a collector with a given type of mirrors (and eventually given gaps between the mirror rows), than the width is a function of the number of parallel mirrors. In a simulation of a collector with given fixed characteristics (tube diameter 7.5 cm, mirror width 50 cm, receiver height above primary mirrors 7.5 m) the following dependency of the levelized electricity costs on the number of mirror lines (N) was determined\(^9\):

![Graph showing dependency of levelized electricity costs on number of mirror lines](Image)

**Figure 13:** Dependency of the levelized electricity costs on the number of primary mirror lines (source: Morin et al. 2003)

The most cost efficient total aperture width, in a system with the indicated characteristics, would be around \(35 \cdot 0.5m = 17.5m\), containing 35 lines of primary mirrors. As easily to be seen, at higher reflection accuracy (geometrical mirror exactness, tracking exactness) the optimal width is slightly larger. Additionally, the levelized electricity costs also depend on the mirror quality (the different colours indicate different geometrical qualities of the mirrors in the primary mirror field, blue is the highest quality, red the lowest). The broader is the collector, the more weight carry the inaccuracies. A higher mirror accuracy favours broader collectors; at higher mirror qualities the optimum is at higher collector widths.

As already indicated, it has to be taken into account that the values in the diagram (this holds also for the other diagrams below) are valid only under certain conditions and they are the result of a concrete simulation. We use them here just to illustrate that there is a certain optimum concerning the considered parameters.

- The distance of the absorber tube from the mirror plane should neither be too large nor too small. Once more, very distant mirrors contribute less to the radiation concentration and their projective efficiency is more sensible to geometrical mirror errors and tracking inaccuracy. On the other hand, if the absorber tube is situated at a very short distance, shading and blocking between the primary mirrors will be stronger and the incidence angles on the receiver will be very big. The following figure shows the dependency of the levelized electricity costs on the height (H) of the absorber tube in relation to the Fresnel mirror plane. The simulation is made for a collector with 34 parallel primary mirror lines (50cm width each). Once more the dependency is illustrated in relation to the reflection accuracy. The optimal height is between 8 and 11 m. PE 1 operates with a height of 7.40m. The optimal height may be larger for systems with a higher optical accurateness. At very small heights, the levelized electricity costs increase strongly.

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\(^9\) See Morin et al. 2003.
costs are less dependent on the reflection accuracy because of the shorter way of the reflected light from the mirrors to the receiver. Blocking and shading among the different mirror rows (which does not depend on the mirror quality) is the principal reason of the rising electricity costs.

Figure 14: Dependency of the levelized electricity costs on the height of the absorber tube above the primary mirror plane (source: Morin et al. 2003)

- The gaps between the mirror rows should not be too big. Large gaps imply a large collector width with distant mirrors without aperture area gains. On the other hand, the gaps should not be too small because small gaps imply higher shading and blocking between the mirror rows. The following figure shows the dependency of the levelized electricity costs on the gap width between the mirror rows. Once more it is to be seen that the optimum for systems with high reflection accuracy is at larger gaps than the optimum for systems with lower reflection accuracy.

Figure 15: Dependency of the levelized electricity costs on the gaps between the mirror lines (source: Morin et al. 2003)

- Finally, the curvature of the mirror stripes is a parameter that has to be considered. It is obvious that the curvature should have a radius that is neither too large nor too small. In both cases a larger part of the radiation would miss the receiver. The intercept factor will be maximal for a certain value in between. The following figure shows the dependency of the levelized electricity costs on the focal length of the mirror stripes.
Figure 16: Dependency of the levelized electricity costs on the curvature of the mirrors, given in relation to the distance to the absorber tube (source: Morin et al. 2003)

The focal length is given in relation to the distance from the absorber tube \( \frac{f}{\sqrt{x^2+y^2}} \).

Obviously, the optimum must be situated near 1 independently on the geometrical quality of the system. However, it is not situated exactly at 1 because of the mirror astigmatism. Remember that the Sun changes its position over the day transversally in relation to the mirror stripes. That’s why it is impossible that the radiation is concentrated all over the day onto a clear cut focal line. Take a parabolic trough and move it such that the Sun is not within the optical axis plane. In this case the focal point is changed to a caustic as to be seen in the following figures:

![Figure 17: Focal point (left) and caustic (right) at a parabolic trough cross-section in accordance with the incidence angle (source: Mertins 2009, 23)](image)

Because of the peculiarity of Fresnel power plants that the radiation generally does not hit the mirrors perpendicularly and that the incidence angle (also in the transversal dimension) changes over the day the ideal focal length of the mirror stripes does not correspond exactly to the distance of the absorber to the mirrors. The ideal focal length was calculated to be about 1.1 times the mirror-absorber distance. As to be seen in the figure, a relative focal length below 1 has stronger negative effects than a relative focal length beyond 1.1.

The phenomenon of astigmatism limits also the width of the mirror stripes. The broader the mirrors the more weight carries the astigmatism problem.
We will have a look now on the influence of the angle of incidence of the incoming direct solar radiation on the Fresnel collector. Contrary to the parabolic trough collector, where the incidence angle varies only in one dimension (transversally to the trough), the incidence angle on the Fresnel collector varies transversally as well as longitudinally. The cosine effect, but also the shading and blocking between the mirror rows and the shading between the receiver and the mirrors, reduce the energy yield. The following figure shows the correction factor that was determined for a collector of the German company Industrial Solar. The energy yield at vertical incidence is taken as the reference value.

![Figure 18: Correction factors for the energy yield at an Industrial Solar Fresnel collector for different incidence angles in transversal and longitudinal dimension (source: Industrial Solar)](image)

Longitudinal deviation from the vertical incidence has a larger effect on the energy yield than transversal deviation. For transversal incidence angles up to 50° the reduction effect is very small, and for high transversal incidence angles, even at 90°, i.e. at horizontal incidence, the mirrors still reflect some radiation onto the receiver. Nevertheless, the reduction of the reflected radiation that reaches the receiver at high transversal incidence angles is one reason why the solar-to-electric efficiency of Fresnel power plants does not reach the efficiency of parabolic trough power plants. Remember that the transversal incidence angle at a parabolic trough has always the ideal value zero, because the whole collector construction tracks the Sun.

The different incident angle effects in the transversal and longitudinal dimension are important for the determination of the solar field orientation. Theoretically, it is possible to orient the Fresnel solar field in whatever direction.

In relation to north-south orientation and east-west orientation, the incident angle effects imply the following differences. We refer to a typical Sun Belt location, i.e. a location between the latitudes of 15° and 40°, for instance southern Spain or a MENA country:

- North-south orientation permits a more equilibrate energy yield over the day. It is even possible to utilize the radiation available right after sunrise and right before sunset.
- East-west orientation permits a more equilibrate energy yield over the year because the high incidence angles in winter carry less weight than in a north-south orientation.
- East-west orientation provides the highest power peaks.

These qualitative results, which coincide with parabolic troughs, do not say anything about the annual energy yield. In Sun Belt locations, the annual energy yield is bigger for north-south orientation,
which is also the case in parabolic trough solar fields. The following two figures show the results of simulations that were done by Industrial Solar for a Fresnel system in Farafra/Egypt. The studied solar field has an aperture area of 3872 m² and consists of 176 modules in 11 collector strings. The first figure shows that the east-west orientation achieves the highest peak power.

![Graph showing number of operating hours per year at different collector power ranges for north-south and east-west orientation](source: Schwind/Zahler 2009, 18)

**Figure 19:** Number of operating hours per year at different collector power ranges for north-south and east-west orientation (source: Schwind/Zahler 2009, 18)

The second figure shows that the energy yield is more equilibrated in east-west orientation than in north-south orientation. It is also visible that the annual energy yield is higher in systems with north-south orientation than in systems with east-west orientation:

![Graph showing monthly heat production per aperture area](source: Schwind/Zahler 2009, 19)

**Figure 20:** Monthly heat production per aperture area (source: Schwind/Zahler 2009, 19)

The annual heat production for the whole system was calculated to be 4288 MWh (or 1107.4 kWh per m² aperture area) for north-south orientation and 3808 MWh (or 983.5 kWh per m² aperture area) for east-west orientation. That means that the annual heat output of the east-west oriented system at the

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mentioned location amounts only to about 88% of the annual heat output of the north-south oriented system.

![Graph showing annual energy yield per square meter aperture area]

**Figure 21:** Annual energy yield per square meter aperture area

Existing and planned power plants opted for north-south orientation.

The Fresnel power plants that are built until now or are in construction apply direct steam generation, i.e. the steam is generated directly in the solar field without any heat transfer medium in between. Direct steam generation systems can be realized for saturated as well as for superheated steam generation. Superheated steam generation is technically more challenging. Saturated steam generation is simpler, but it implies lower system efficiencies.

The first commercial Fresnel power plants, the Novatec Solar power plants, generate saturated steam. A steam drum between the solar field and the power block is the steam/water separator and at the same time a short time storage that allows the bridging of transient cloudiness.

In the case of superheated steam generation, the solar field is divided into three sections: preheating section, evaporation section and superheating section. The evaporation section is by far the largest part because the evaporation process needs the most energy.

![Diagram showing field structure in a superheated steam generating field]

**Figure 22:** Field structure in a superheated steam generating field (source: Häberle 2002)

Fresnel collectors cannot only be used for electricity generation, but they are also appropriate for small scale heat generating systems. Due to their simple structure, their low height and their high ground use efficiency they can be installed also on buildings for solar heating or cooling.
Figure 23: Large scale and small scale applications of the Fresnel technology (source: Novatec Solar, Industrial Solar)
3.2 Receiver

The receivers of the realized Fresnel systems have another structure than the receivers of parabolic trough power plants. The most eye-catching feature is the existence of a secondary concentrator. But also the absorber tubes are different. In the systems that were realized until now they are much simpler than the absorber tubes in parabolic troughs. The receiver is placed on rollers to compensate the thermal expansion due to the high temperatures during operation. In the case of steel receivers the longitudinal thermal expansion at high operation temperatures amounts to approximately 0.6 %, i.e. 6 m for a 1000 m receiver.

![Different receiver types](image)

**Figure 24:** Different receiver types in the Solarmundo, Novatec Solar and Ausra plants (source: Häberle 2002, Novatec Solar, Ausra)

3.2.1 Secondary concentrator

A Fresnel mirror system alone cannot reach continuously the same radiation concentration like a parabolic trough. At a parabolic trough, the Sun is always situated in the optical axis plane, which is not the case at a Fresnel system. Over the day, the Sun has different positions in relation to the optical axis plane of the system. That’s why it is (even theoretically) impossible to design the curvature of the individual mirror stripes in such a way that there is always a sharp focal line for parallel radiation. So, contrary to parabolic trough receivers, means are necessary to mitigate the unavoidable optical inaccuracy of the Fresnel collector and to improve the intercept factor. This can be done by a secondary concentrator that is allocated above the receiver tube(s). The secondary concentrator has, hence, principally the task to increase the intercept factor. But, thereby it has also the effect that the concentration ratio gets higher.

In the case of the Novatec Solar systems, the secondary concentrator amplifies the width of the target area of the radiation from 7 cm (absorber tube diameter) to 30 cm (secondary reflector width). The secondary concentrator increases the intercept factor without increasing the absorber diameter. That
means that the incoming radiation is used more efficiently without generating higher thermal losses at a larger absorber tube.

The secondary concentrator in the Novatec Solar plant is designed as a compound parabolic mirror whose focal points lie within the absorber tube. Besides the high reflectivity of the secondary concentrator and an appropriate concentrating geometry the (mechanical and optical) heat resistance of the system is a special challenge because the temperatures within the receiver cavity reach 300°C. The secondary concentrator is made out of front surface mirrors. This is possible because the mirror is located within the receiver which protects it. Front surface mirrors have the advantage of a higher reflectivity because the light does not traverse an additional glass layer.¹¹

![Figure 25: Novatec Solar single-tube receiver with compound parabolic shaped secondary concentrator (source: Novatec Solar)](image)

The receiver of the Ausra system is different from the Novatec Solar receiver. While the latter has one absorber tube and needs therefore a secondary concentrator mirror with an exact concentrator geometry, Ausra opted for a multi-tube receiver. This has the advantage that the absorber area is larger. In this system, the secondary concentrator does not have the same importance as it has in the Novatec Solar system. The Ausra receiver has a trapezoidal form with a corresponding simple secondary concentrator geometry:

![Figure 26: Ausra multiple tube receiver with simple trapezoidal secondary reflector (source: Ausra (left))] (image)

Besides the radiation concentration, the secondary concentrator has some additional functions:

¹¹ See Morin 2008.
- It serves as a thermal insulator. The convective flow is obstructed because it covers the absorber tubes from above. Additionally, a glass pane below allows the entrance of the reflected radiation, but reduces the convective heat exchange with the environment. Furthermore, the glass pane also reduces the radiative heat loss because the transmittance of glass is low for the infrared spectrum. The secondary concentrator has also an insulating layer that reduces the heat loss through the reflector material. The multiple insulation effects of the secondary concentrator allow the use of much simpler absorber tubes compared to the absorber tubes in parabolic trough power plants. While parabolic trough power plants use absorber tubes with a vacuum insulation, Fresnel systems until now use absorber tubes without vacuum insulation.

- It represents a structural element that stabilizes the receiver. This is a very important function taking into consideration that the Fresnel power plant receivers already now reach a length of nearly 1 km.

![Figure 27: Receiver of the PE 1 plant (source: Novatec Solar)](image)

- It protects the absorber tube(s) against weathering.

### 3.2.2 Absorber tube

As already mentioned, until now the receiver tubes of Fresnel power plants are simpler as the receiver tubes of parabolic power plants. The secondary concentrator serves additionally as a thermal insulator. That’s why until now receivers are used that did not have a vacuum insulation, which is common in parabolic trough technology. Fresnel receivers with vacuum insulation are currently under development.

Like in parabolic troughs, the absorber tubes have a selective coating that has a high absorptance at short wave lengths and a low emittance for infrared radiation. The ISE Fraunhofer Institute in Freiburg/Germany developed a tube for Fresnel power plants with a cermet coating. Cermet is a composite material composed of ceramic (cer) and metallic (met) materials. The coating has been proven to be stable until more than 450°C. The cermet layer, together with an antireflective layer, permits the high absorption of solar radiation, while a metallic layer reduces the emittance in the infrared range.

The tubes themselves are made out of stainless steel.
As already mentioned, Ausra uses multiple-tube receivers, while Novatec Solar and Industrial Solar use single-tube receivers. Tests showed that the single-tube receivers allow a slightly better energy yield.\textsuperscript{12}

\textsuperscript{12} See Morin et al. 2003, 2.
Novatec Solar has now the plan to use also vacuum insulated absorber tubes in order to reach higher temperatures. The company is developing a new generation of Fresnel solar fields (SuperNOVA) that will operate at 450°C. This will increase considerably the system efficiency, but it will also imply higher system costs.

Absorber tubes for direct steam generating Fresnel power plants generally have to resist higher pressures than the absorber tubes for common parabolic trough power plants, which are operated in indirect steam generation mode. Direct steam generation implies that the pressure energy is directly generated in the absorber tubes, while indirect steam generation permits the operation of the solar field under low pressures. Therefore, common parabolic trough power plant receivers cannot be used directly in Fresnel power plants if they are to be operated at pressures as for instance 55 bar, which is the operation pressure of Novatec Solar’s PE 1 and PE 2. The common Schott parabolic trough receivers are designed for a maximum pressure of 40 bar and the Archimede parabolic trough receivers are designed for an operating pressure of until 20 bar.

### 3.3 Tracking system

Like parabolic troughs, Fresnel collectors have a single axis tracking. The angle that is permanently modified is the tilt angle $\varphi_t$. This angle is different for the different mirror rows.
Figure 30: Mirror tilt angle and its determinants

\( \varphi_i \) is determined by the angle \( \beta_i \) and the transversal solar altitude angle \( \alpha_T \). The angle \( \beta_i \) on its part is determined by the distance \( d_i \) of the respective mirror row from the middle axis of the collector and by the height \( h \):

\[
\varphi_i = \frac{\alpha_T - \beta_i}{2}, \quad \beta_i = \arctan \frac{h}{d_i}
\]

\[
\varphi_i = \frac{\alpha_T - \arctan \frac{h}{d_i}}{2}.
\]

The derivation with respect to time is

\[
\frac{d\varphi_i}{dt} = \frac{\frac{d\alpha_T}{dt} - \arctan \frac{h}{d_i}}{2} = \frac{1}{2} \cdot \frac{d\alpha_T}{dt}.
\]

The temporal variation of \( \varphi_i \), i.e. \( \frac{d\varphi_i}{dt} \), depends only on the temporal variation of the angle \( \alpha_T \), i.e. on the Sun’s apparent movement, not on the mirror position. The different mirror rows have different angular positions, but they move at the same angular velocity. Theoretically, this makes it possible to connect all the mirrors by using quite a simple mechanical coupling and to drive them by a single motor. Nevertheless, the realized Fresnel systems until now opted for individual mirror tracking because it was found to be more accurate and because a gradual defocusing for heat dumping at irradiance peaks is easier with individual driving motors.

The transversal solar altitude angle \( \alpha_T \) can be determined by the solar altitude angle \( \alpha_s \) and the azimuth angle \( \gamma_s \). We suppose a north-south oriented collector:
Figure 31: Determination of the transversal solar altitude angle

\[ \tan \alpha_T = \frac{a}{b} = \frac{\tan \alpha_s \sqrt{b^2 + c^2}}{b} = \frac{\tan \alpha_s \sqrt{b^2 + \left( \frac{b}{\tan \gamma_s} \right)^2}}{b} = \tan \alpha_s \cdot \sqrt{1 + \frac{1}{\tan^2 \gamma_s}} = \frac{\tan \alpha_s}{\sin \gamma_s} \]

\[ \tan \alpha_T = \frac{\tan \alpha_s}{\sin \gamma_s} \]

It holds \(0^\circ \leq \alpha_T \leq 180^\circ\) and \(\alpha_T = 90^\circ\) at \(\sin \gamma_s = 0\).

Compared to parabolic trough collectors, the tracking system of Fresnel collectors has the advantage to need lower forces to move the mirrors. The mirrors are much smaller and the mirror structure can be designed easily in such a way that the centre of gravity is within the rotational axis so that motors and gears can be quite simple.

The following figures show two possibilities how to achieve that the centre of gravity of the mirror constructions is within the rotational axis. There is the Ausra solution on the one hand that integrates the mirror in a circular structure and there is the Solarmundo solution on the other hand that uses an asymmetrical structure in order to maintain the centre of gravity closed to the rotational axis.\(^{13}\)

\(^{13}\) See Häberle 2002.
3.4 Steam drum

A steam drum is not really a special Fresnel power plant component. However, it is a characteristic element of the Fresnel power plants that were built until now. These power plants are operated in direct steam generation mode. They need, hence, a water/steam separator within the solar field or between the solar field and the power block. In superheated steam systems it is integrated into the solar field between the evaporation section and the superheating section as a steam/water separator. In saturated steam systems it is located between the solar field and the power block. In the case of saturated steam systems the steam drum serves additionally as a short-time storage. It makes more stable the power flow and bridges transient cloudiness. Parabolic trough power plants with thermo oil as heat transfer fluid have a certain thermal inertia due to the thermo oil that is distributed over the solar field. In the case of directly steam producing plants, the thermal inertia of the solar field is much lower. The integration of a steam storage increases the thermal inertia and allows that the turbine goes on working at sliding pressure conditions if direct solar radiation is interrupted temporarily.
Figure 33: Power block of PE 1 with steam storage (source: Novatec Solar)
4. Disadvantages and advantages over parabolic trough power plants

Fresnel power plants are in a competitive situation with parabolic trough power plants. In the foregoing sections, a comparison to parabolic troughs was already drawn at several points. In this section we shall present in a concentrated form the advantages and disadvantages of Fresnel power plants over parabolic trough power plants.

Roughly, the advantages of Fresnel power plants are the considerably lower investment costs for the solar field (at the same aperture area)\textsuperscript{14} and, hence, of the whole power plant (at the same nominal power), the lower operation and maintenance cost and the higher land use efficiency. The disadvantage is that the solar-to-electric efficiency is still lower. The question, which has to be answered in order to estimate the future perspectives of these two power plant types, is, then, which of these characteristics carries more weight.

Until now there are no reliable data for Fresnel power plants, because up to now there is no large Fresnel plant in operation. The first large plant, Novatec Solar’s PE 2 with 30MW, is still under construction. An estimation made in 2002 after the construction of the Solarmundo collector in Liège/Belgium claimed a total cost reduction for the solar field of nearly 50% in relation to the solar field of a parabolic trough power plant (measured in €/m\textsuperscript{2} of aperture area).\textsuperscript{15} MAN Ferrostaal claims the total cost reduction for the whole power plant to be up to 30%.\textsuperscript{16}

In the year 2004, the ISE Fraunhofer Institute in Freiburg made a simulation of a 50MW Fresnel power plant with a 50MW parabolic trough power plant.\textsuperscript{17} Simulation programs were used (Greenius and ColSim) to calculate the energy yield. Solar field costs were determined as being 220€/m\textsuperscript{2} for the parabolic trough power plant and 150€/m\textsuperscript{2} for the Fresnel power plant. According to this simulation, the levelized energy costs of the electricity generated in a Fresnel power plant are lower than the costs of the electricity generated in a trough power plant. The difference varies between 17% and 8%. The higher differences belong to locations where the radiation conditions are rather weak (17% were calculated for about 1850kWh/m\textsuperscript{2}a, which is the case in Murcia/Spain), while the low differences belong to locations with excellent radiation conditions (about 3070 kWh/m\textsuperscript{2}a, which is the case in Aswan/Egypt). The reason why Fresnel power plants have more advantages at locations with a lower DNI is that a power plant at such a location needs a larger solar field so that the lower solar field costs for Fresnel power plants carry more weight.

\textsuperscript{14} We can define the aperture area of a Fresnel solar field, following the proposal in Häberle 2002, as the sum of the primary reflector area.
\textsuperscript{15} See Häberle et al. 2002.
\textsuperscript{17} See Lerchenmüller et al. 2004.
In the year 2009, DLR made a comparative study also between a 50 MW linear Fresnel power plant and a 50 MW parabolic trough power plant. Contrary to the Fraunhofer study, direct steam generating systems are considered. The study takes the Fresnel collector at the PSA as the power plant collector type for the Fresnel power plant and the Eurotrough for the parabolic trough power plant. Live steam parameters and power block performance are identical for both systems and the plants do not count with a storage system. The study assumes that the uncertainties regarding the costs of a commercial linear Fresnel power plant are large, because no large plant has been built when the study was conducted. It was therefore decided not to use any costs that were defined in advance for the Fresnel solar field. Instead it was calculated what the specific investment costs of the linear Fresnel collector could be in order to be able to achieve the same electricity production costs like the parabolic trough power plant. The solar field size was chosen in such a way that the lowest LCOE resulted in each case. Performance models were applied to calculate the annual electricity yield for each plant. Contrary to the other study, the comparison was done for a determined DNI; Barstow/California was taken as plant site.

The result was that the solar field of a linear Fresnel power plant must achieve installation costs of about 55% of the specific installation costs of a parabolic trough field (measured in €/m² of aperture area) in order to enable a Fresnel power plant to reach the same LCOE like a parabolic trough power plant and, hence, to be cost-competitive with it. The result is represented in the following figure. The diagram is generated by the variation of the specific solar field costs of the Fresnel power plant in relation to the specific solar field costs of the parabolic trough power plant. All parameters that appear in the figure are related to the respective values for the parabolic trough power plant. The most important line in our context is the light blue line, which indicates the mentioned result that the Fresnel solar field must cost about 55% of the parabolic trough solar field (measured in €/m² of aperture area) in order to reach cost-competitiveness (measured in LCOE). What is to be seen additionally is that the aperture area of a Fresnel power plant is larger than the aperture area of a parabolic trough power plant.

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19 There is another study, where some parameters in the Fresnel solar field are modified (changes in the bearing structure and in the receiver), which allow higher Fresnel solar field costs to reach the same LCOE like the respective parabolic trough tower plant (Morin et al. 2009).
with the same rated power. The land requirement, however, is lower. The annual net electric output is lower as well as the net efficiency.

![Graph showing influence of relative solar field costs on different power plant parameters](image.png)

**Figure 35:** Influence of the relative solar field costs of the linear Fresnel power plant on different power plant parameters (source: Dersch et al. 2009)

Both studies are based, however, on simulation. There may be more reliable data in the near future when Novatec Solar’s plant PE 2 will start operation.

### 4.1 Disadvantages

The efficiency disadvantage of Fresnel power plants over parabolic power plants is principally caused by optical losses. The Fresnel collector does not follow the Sun, as it is the case with parabolic troughs. What tracks the Sun are the individual mirrors or mirror rows. This implies some optical losses that do not exist (or that do not exist in the same sense) at parabolic troughs:

a) Fresnel collectors do not have only longitudinal cosine losses, but they are affected also by transversal cosine losses. Parabolic troughs, on the contrary, have only longitudinal cosine losses. Transversal losses do not exist because of the tracking of the complete trough. This is the most important additional optical loss factor at Fresnel collectors in comparison to parabolic troughs.

b) The parallel mirror rows shade each other at high transversal incidence angles. They also block parts of the reflected radiation at high transversal incidence angles.
c) It is impossible to reach ideal mirror curvatures because the transversal incidence angle on them changes over the day. The resulting astigmatism in the Fresnel field is unavoidable. However, this problem is mitigated by the secondary concentrator and/or by a broader multi-tube receiver, which amplifies the radiation target size. Of course, this happens at the expense of one reflection step more (in the case of a secondary concentrator), which implies an additional loss and/or of the increase of the absorber surface area, which causes higher thermal losses. The additional reflection loss in the secondary concentrator, however, is maintained very low by using front size mirrors so that no additional glass layer must be traversed.

The little experience that exists with Fresnel power plants is, at the same time, an additional disadvantage for them (which does not have to do with the technology itself): It is still considered as a less proven technology, which is, therefore, sometimes considered as less reliable and which may have more difficult financing conditions.

### 4.2 Advantages

We come now to the advantageous properties of Fresnel power plants in comparison to parabolic trough power plants.

#### 4.2.1 Fixed receiver

A group of advantages is related to the fact that the receiver is fixed and not connected to the moving parts of the collector and that it does not follow the tracking movements of the mirrors:

- Fresnel power plants do not need movable high pressure joints between the absorber tubes, which are a constructive challenge in parabolic trough power plants. This allows lower costs and a less vulnerable heat transfer system.

- Collectors and absorber tubes can be very long. Novatec Solar’s PE 1 reaches already 806 m and PE 2 will reach more than 940 m. Such long collectors allow the reduction of direction changes of the water/steam flow, which reduces pressure losses in the tubes. It also reduces the number of loops and tube connections between them.

- The stable position of the absorber tube and the mirror stripes make possible that the radiation distribution at the absorber tube is quite constant. Additionally, most radiation hits the absorber tube from below, which is an advantage for the direct steam generation, where the liquid phase flows rather in the lower part of the absorber tube.

- Fresnel power plants can be operated more easily in the direct steam generation mode. The first installed prototype systems (Solarmundo, PSA) are operated in the direct steam generation mode.
generation mode as well as the first commercial systems (Ausra systems and PE 1 and PE 2 by Novatec Solar).

**4.2.2 Direct steam generation**

As mentioned, thanks to the fixed absorber tubes, direct steam generation (DSG) is more easily applicable in Fresnel power plants than in parabolic trough power plants. DSG for parabolic trough power plants is currently applied for the first time in a commercial power plant in Thailand. Until this plant, only investigation and development projects were realized. In Fresnel power plants, on the contrary, DSG was chosen right from the beginning. Direct steam generation has several advantages:

- Steam as heat transfer fluid allows higher temperatures because there is no danger of thermo oil cracking. Novatec Solar is planning a new Fresnel power plant generation that operates at 450 °C.
- The number of construction components can be reduced because no heat exchange has to be realized between a solar field heat transfer fluid (thermo oil) and Rankine cycle working fluid (water/steam).
- The thermo oil itself is an expensive component of CSP plants so that the lack of thermo oil is a direct economic advantage.
- As there is no heat transfer between two heat transfer fluids, there is one thermal loss factor less.
- The usage of steam as a heat transfer fluid may reduce the mean heat transfer fluid temperature in the absorber tube (even at higher final temperatures) and reduce, hence, thermal losses. This reduction is possible because in a large part of the receivers the boiling process is realized, which takes place at a reduced temperature. Only in the small part, where the superheating of the steam is realized (if there is superheating), high temperatures are reached.
- Water has further advantages in comparison to other HTFs: It is environmentally friendlier than thermo oil so that leakages in a directly steam generating plant do not imply major environmental dangers. It is less corrosive than salt. Its freezing temperature is much lower than the freezing temperature of salt and even slightly lower than of thermo oil. The effort required to ensure adequate anti-freeze protection is reduced significantly.

A problem of DSG is still that there are no commercially available large storage systems. Until now, only short time steam storages for DSG systems with saturated steam generation are commercially applied. A large storage system for DSG should be a modular storage with sensible heat storage modules for preheating and superheating (if there is superheating) and a latent heat storage module for evaporation. DLR is currently testing an appropriate storage system in a demonstration parabolic trough DSG loop in the Endesa power plant in Carboneras.

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20 It is estimated that direct steam generation in parabolic troughs under favourite conditions could lead to a reduction of electricity costs of more than 10% if the operation temperature of 500°C is reached (compared to the 370°C, which is the operating temperature of existing parabolic trough power plants). See Feldhoff et al. 2009.

21 The heat transfer fluid for the Andasol parabolic trough power plants account for 5% of the total investment costs (IEA 2010, 27).

22 See Laing et al. 2011.
4.2.3 Flat mirrors and plane collectors

The usage of flat mirrors and plane collectors has the following positive effects:

- The use of flat mirrors allows a cost reduction compared to curved mirrors. The mirror stripes are curved slightly in the collector space frame, but the stripes themselves are flat. Parabolic troughs, on the contrary, need mirrors that are already produced in a curved form.

- Cleaning is simpler for Fresnel mirrors than for parabolic troughs.

- The alignment of the mirror stripes in one plane has the advantage that wind loads are reduced. That means that the power plant is less susceptible to wind damages than parabolic trough power plants. Space frame and tracking mechanism do not need to resist the same mechanical loads. This also makes possible the use of broader collectors. Optical exactness, but not mechanical loads, is the limiting factor for the collector width. Novatec Solar’s PE 2 has an aperture width of 12m, while the Eurotrough parabolic collector has an aperture width of less than 6m. That means that a Fresnel power plant needs less receiver length per aperture area unit.\(^{23}\)

- The planarity of the reflector allows that collectors can be placed one besides the other without leaving much space in between. Parabolic troughs, on the contrary, need always quite a large space between the collectors (about the double of the collector width) in order to avoid mutual shading and blocking in the morning and in the evening. This implies higher land use efficiencies for Fresnel power plants than for parabolic trough power plants and, indeed, than for any other kind of CSP plants. For a location with good solar radiation conditions (southern Spain) a land use of 4-6 m\(^2\)/MWh\(_{y}\) is reached, while a parabolic trough power plant needs 6-8 m\(^2\)/MWh\(_{y}\).\(^{24}\) Point-focussing systems have higher land use requirements.

- An additional aspect concerning land use efficiency is that the Fresnel collectors offer the possibility to make a multiple use of the solar field area. The semi-shaded space below the Fresnel system could be used for agriculture in semi-desert or desert environments. It is protected against excessive evaporation and sheltered from the cold desert sky at night making possible an agricultural use where natural conditions normally would not permit it.

\(^{23}\) The aperture width of a collector is the sum of the width of the primary mirrors in the collector. The Solarmundo prototype even used an aperture width of 24m.

\(^{24}\) See Müller-Steinhagen/Trieb 2004.
The tracking system may also be quite simple. First, the motors and gears do not need to resist high mechanical loads. The mirror stripes are much smaller and lighter than whole parabolic mirrors. Additionally, the angular changes of the different stripes are always the same so that the coordination of their tracking movements does not present additional problems. It is even possible to drive all mirror stripes with one motor and a simple transmission gear.

4.2.4 Simple absorber tubes

As the receivers of Fresnel power plants contain a secondary concentrator that, together with a glass pane, functions additionally as a thermal insulation, the absorber tubes themselves can be much simpler than in parabolic trough power plants. Especially, they do not need a vacuum insulation. That’s why no metal-glass sealing is needed, which was a major challenge in the construction of parabolic trough receivers, and no vacuum technology needs to be applied.

The first power plants, which were constructed by Ausra and Novatec Solar, use simple absorber tubes with a selective coating. However, Novatec Solar is now developing a new power plant generation, which would use vacuum insulated absorber tubes in order to reach higher operation temperatures and higher solar-to-electric efficiencies.

However, parabolic trough receivers cannot be used directly in Fresnel power plants because these plants are designed for direct steam generation and, and their receivers have to resist higher operating pressures than parabolic trough receivers (PE 1 and PE 2: 55 bar). Common parabolic trough receivers are designed only for 20 bar (Archimede) or 40 bar (Schott).

5. Hybridisation

The linear Fresnel systems that were built until now are direct steam generation (DSG) systems. As mentioned above, no large storage systems exist until now for DSG systems. There are only short time steam storages for saturated steam systems. The electricity generation in Fresnel power plants (as far as they are operated in the DSG mode) is therefore quite directly dependent on the available solar radiation. It cannot shift the power generation from a time with good radiation availability to a time with low or no radiation availability. A general important advantage of CSP technologies in comparison to, say, PV, namely to generate power on demand, applies only in quite a weak sense to linear Fresnel power plants. A possibility to recover this advantage is hybridisation. The quite straightforward possibility of hybridisation is given for all CSP technologies because thermal power from the radiation concentration can be combined with thermal power from other sources, especially from fuel combustion.

The first commercially applied linear Fresnel system was a solar field that was built to supplement the heat supply of a coal power plant. As mentioned in the overview over the history of Fresnel technology in Liddell, Australia, a small solar field (1 MWth) was built by Ausra in the local coal power plant. It was the first CSP system for fuel saving in a coal-fired power plant. The steam that is generated in the Fresnel collector is combined with the steam that is generated by coal combustion. Until 2008 the solar field was amplified to 9 MWth. It is announced that another Fresnel solar field will be built by Novatec Solar, which will double the solar thermal capacity. The Liddell power plant is a very large coal power plant (4 power blocks with 500 MW each) with a very small solar share. Hybrid systems, where Fresnel solar field and combustion unit have a more similar capacity do not exist until now, but investigations have been done. One proposal is the combination of a Fresnel solar field with a parallel biomass boiler, where the Fresnel solar field
provides a maximum of 50% of the live steam for the power block. The biomass boiler reacts to the solar radiation maintaining the plant power at a constant value. What made this idea interesting was the complete system dependence on renewable energy sources and the fact that the typical steam parameters of a biomass plant correspond to those of the Fresnel collector (approximately 450°C and 70 bar). The plant can be operated 24 hours a day at its rated power without the need for heat storage. Compared to solar only plants, the efficiency of converting solar radiation into electrical energy may be higher in such a plant since the steam cycle always runs at full load. Ausra offers a gas fired back-up for its Fresnel solar steam generators in order to provide firm capacity. However, until now no system has been built.

Theoretically, it would also be possible to integrate a Fresnel solar field into a gas-fired combined cycle plant and to provide additional steam for the steam cycle (Integrated Solar Combined Cycle System, ISCCS). But, until now this configuration has not been taken into account. All ISCCS that are built currently and that are planned contain parabolic trough solar fields. However, the Fresnel technology is still very young and it can be expected that more power plant configurations with Fresnel solar fields will be proposed in the future if the economic advantages of the Fresnel technology over the parabolic trough technology turn out to be sufficient.

25 Lerchenmüller et al. 2004b.
26 See http://www.ausra.com/technology/.
Reference list


Lerchenmüller, H. et al. (2004b): “Fresnel collectors in hybrid solar thermal power plants with high solar shares”.


Questions and exercises

Questions

1) Why did Augustin Jean Fresnel design the first Fresnel lenses for lighthouses and not for, say, binoculars or telescopes?

2) In a small Fresnel mirror application for a solar heating and cooling system, a producer wants to use absolutely flat mirrors. What does this mean for the mirror width to be selected? And what does it mean for the receiver width?

3) Why do the advantages of Fresnel power plants over parabolic trough power plants carry more weight at lower annual DNI than at higher annual DNI?

4) Consider the solar-to-thermal efficiency differences between north-south oriented Fresnel and parabolic trough collectors. When are they larger, in the early morning or at noon?

5) In parabolic troughs, the Sun image at the receiver has a changing width because of the varying distance between the point where a sunbeam hits the mirror and the point where it reaches the receiver (beam spread!). In Fresnel collectors the same phenomenon occurs. However, there is a further aspect that provokes that the Sun image has a changing width and sharpness. What is this additional aspect? How is this effect mitigated?
Answers

1) The Fresnel lens has the advantage that it is much lighter than a “normal” lens. So it is useful, especially, where large lenses are used. This is not the case in binoculars, but, for instance, in lighthouses. The weight reduction is gained at the expense of a lower optical exactness. That means, Fresnel lenses are not used in applications where the optical exactness is crucial like in telescopes or binoculars.

2) These mirrors must be less broad in order to maintain the beam width in an acceptable range. The receiver must be quite broad in order to capture the widened beam. However, it must not be too broad in order to limit the shading that the receiver produces on the collector plane.

3) At lower DNI the solar field must be larger so that the lower prices of the Fresnel power plant have a larger effect than at a location with very good DNI.

4) The differences are larger in the early morning (and in the late evening) because there are hardly cosine losses at parabolic troughs due to the absence of cosine losses in transversal dimension, while there are considerable cosine losses at Fresnel collectors. The fact that there are transversal cosine losses in Fresnel solar fields is the most important factor that provokes that the solar-to-electric efficiency is lower in linear Fresnel power plants than in parabolic trough power plants.

5) Due to the variance of the transversal incidence angle of the direct solar radiation, the mirror focal point of the mirror stripes (if there is any sharp focal point) is widened to a caustic, which makes the Sun image fuzzier. The effect is mitigated by means of a secondary concentrator.
Exercise

The investment for a 50MW parabolic trough power plant is financed with 7% interest rate. Annual operation and maintenance costs amount to 2% (of the investment). Lifetime is considered to be 25 years.

a) Which percentage of the energy output of the parabolic trough power plant has to deliver a 50 MW Fresnel power plant with a lower investment by 30%, other things being equal?

b) Now, consider more difficult financing conditions for the Fresnel power plant being the interest rate 8%, but take a lower annual operation and maintenance amount of only 1% of the investment. Which is now the required annual energy output (in relation to the LEC of the parabolic trough) in order to be competitive with the parabolic trough system?

Use the formula: 
\[
E_y = \frac{I(1+i)^{n-1} + (O&M)_y}{(1+i)^n-1}
\]
Solution

a) \[ LEC_{pt} = \frac{I \cdot (1+i)^n \cdot \left(1 + (0\&M) \right)_y}{E_y} = \frac{I}{E_y} \cdot \left(\frac{(1+i)^n \cdot i}{(1+i)^n - 1} + 0.02\right) \]

\[ LEC_{Fr} = \frac{0.7 \cdot I \cdot (1+i)^n \cdot i + 0.7 \cdot I}{x \cdot E_y} = \frac{0.7}{x} \cdot \frac{I}{E_y} \cdot \left(\frac{(1+i)^n \cdot i}{(1+i)^n - 1} + 0.02\right) = \frac{0.7}{x} \cdot LEC_{pt} \]

\[ LEC_{pt} = LEC_{Fr} \]

\[ x = 0.7 \]

The Fresnel power plant has to deliver 70% of the annual energy output of the parabolic trough power plant.

b) \[ LEC_{pt} = \frac{I \cdot 1.07^{25.07} \cdot 0.07 + 0.02 \cdot I}{E_y} \]

\[ LEC_{Fr} = \frac{0.7 \cdot I \cdot 1.08^{25.08} \cdot 0.01 \cdot 0.7 \cdot I}{x \cdot E_y} \]

\[ LEC_{pt} = LEC_{Fr} \]

\[ \frac{I \cdot 1.07^{25.07} \cdot 0.07 + 0.02 \cdot I}{E_y} = \frac{0.7 \cdot I \cdot 1.08^{25.08} \cdot 0.01 \cdot 0.7 \cdot I}{x \cdot E_y} \]

\[ \frac{1.07^{25.07} \cdot 0.07 + 0.02}{1.07^{25.07} - 1} = \frac{0.7 \cdot 1.08^{25.08} \cdot 0.01 \cdot 0.7}{x} \]

\[ x = \frac{0.7 \cdot 1.08^{25.08} \cdot 0.01 \cdot 0.7}{1.07^{25.07} - 1} \approx 0.68 \]

The Fresnel power plant has to deliver 68% of the annual energy output of the parabolic trough power plant.