Linear Fresnel Collectors

A Technology Overview

SFERA Summer School 2012
June 28, 2012, Almería, Spain

Jan Fabian Feldhoff
E-mail: jan.feldhoff@dlr.de
Overview of CSP Systems

Up to 550 °C, Steam Turbines
- Parabolic Trough

Up to 1000°C, Gas Turbines/Motors
- Solar Tower
- Dish-Stirling

Linear Fresnel
Why a special session about Fresnel?

- Similar to parabolic trough, but...
- ...fixed receiver pipe while mirrors track
- ...trough shape “split” into multiple small mirror facets
- ...lower optical performance
- ...(probably) less expensive
Overview

1. The Linear Fresnel Principle
2. Optical characteristics of Linear Fresnel Collectors (LFC)
3. Performance characteristics of LFCs
4. Components of LFCs
5. Overview existing LFC Plants
6. Outlook on LFC Developments
7. Final Remarks
Fresnel Principle

- Augustin Jean Fresnel (1788–1828), French Physicist
- Thin (low-weight and low-volume) lens for short focal lengths
- First application in lighthouses: to focus light horizontally and make it visible over greater distances

Fresnel Principle > Linear Fresnel Collectors (LFC)
Optical Characteristics of LFC

- Angle Definitions
- Calculation formula
Solar Optics of LFC > Solar Angle Definitions

<table>
<thead>
<tr>
<th>Solar azimuth</th>
<th>$\gamma$</th>
<th>°</th>
<th>The angle between North and the solar position projected on the horizontal plane; $0^\circ \leq \gamma \leq 360^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar elevation</td>
<td>$\alpha_s$</td>
<td>°</td>
<td>Vertical angle between straight line to the sun and horizontal plane</td>
</tr>
<tr>
<td>Zenith angle</td>
<td>$\theta_z$</td>
<td>°</td>
<td>Complementar angle to $\alpha_s$; $\theta_z = 90^\circ - \alpha_s$</td>
</tr>
<tr>
<td>Collector azimuth</td>
<td>$\gamma_c$</td>
<td>°</td>
<td>Angle between North and the aperture orientation</td>
</tr>
<tr>
<td>Collector axis tilt</td>
<td>$\beta_c$</td>
<td>°</td>
<td>Tilt angle between collector surface and horizontal plane; Usually $0 \leq \beta_c \leq 360^\circ$</td>
</tr>
<tr>
<td>Angle of incidence</td>
<td>$\theta$</td>
<td>°</td>
<td>Angle between straight line to the sun and collector normal</td>
</tr>
</tbody>
</table>

Declination  | $\delta$ | ° | Angle between sun beams and equatorial plane of the earth; Positive in summer (between end of March and end of September); $-23.45^\circ < \delta < 23.45^\circ$. |
Hour angle  | $\omega$ | ° | Angle between the meridian of the observer and the meridian parallel to the sunbeams; Negative in the morning; 0 on solar noon; $-180^\circ < \omega < 180^\circ$ |
Geographic latitude  | $\phi$ | ° | Positive on the northern hemisphere; $-90^\circ < \phi < 90^\circ$ |
Geographic longitude  | $\lambda$ | ° | Positive eastward from Greenwich; $-180^\circ < \lambda < 180^\circ$ |
Solar Optics of Parabolic Trough Collectors

<table>
<thead>
<tr>
<th>Solar azimuth</th>
<th>$\alpha_s$</th>
<th>The angle between North and the solar position projected on the horizontal plane; $0^\circ \leq \alpha_s \leq 360^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar elevation</td>
<td>$\alpha_e$</td>
<td>Vertical angle between straight line to the sun and horizontal plane</td>
</tr>
<tr>
<td>Zenith angle</td>
<td>$\theta_z$</td>
<td>Complementary angle to $\alpha_s$; $\theta_z = 90^\circ - \alpha_s$</td>
</tr>
<tr>
<td>Collector azimuth</td>
<td>$\phi_c$</td>
<td>Angle between North and the aperture orientation</td>
</tr>
<tr>
<td>Collector axis tilt</td>
<td>$\beta_c$</td>
<td>Tilt angle between collector surface and horizontal plane; Usually $0 \leq \beta_c \leq 360$</td>
</tr>
<tr>
<td>Angle of incidence</td>
<td>$\theta$</td>
<td>Angle between straight line to the sun and collector normal</td>
</tr>
</tbody>
</table>
Solar Optics of LFC > Main Angles

- **Transversal angle** $\theta_{\text{trans}}$  
  Angle between zenith and projection of straight line to the sun into the transversal plane

- **Longitudinal angle** $\theta_{\text{long}}$  
  Angle between zenith and projection of straight line to the sun into the longitudinal plane

- **Incidence angle** $\theta_i$  
  Angle between straight line to the sun and section line of intersection between incidence plane and transversal plane

- Transversal and incidence angle are used to characterize optical behavior of LFC (since relevant optical effects are best described by these two angles)
Solar Optics of LFC > Angle Definitions

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Angle</th>
<th>Further Description in enerMena report, section III.4.</th>
</tr>
</thead>
<tbody>
<tr>
<td>arbitrary</td>
<td>$\cos \theta$</td>
<td>III-12 [ \sqrt{1 - (\cos(\alpha_s - \beta_c) - \cos \beta_c \cos \alpha_s [1 - \cos(\gamma_s - \gamma_c)])^2} ]</td>
</tr>
<tr>
<td></td>
<td>$\tan \theta_{\text{trans}}$</td>
<td>III-13 [ \frac{\cos \alpha_s \sin(\gamma_s - \gamma_c)}{(\sin(\alpha_s - \beta_c) + \sin \beta \cos \alpha_s [1 - \cos(\gamma_s - \gamma_c)])} ]</td>
</tr>
<tr>
<td>North-south</td>
<td>$\cos \theta$</td>
<td>III-14 [ \sqrt{1 - \cos^2 \alpha_s \cos^2 \gamma_s} ]</td>
</tr>
<tr>
<td></td>
<td>$\tan \theta_{\text{trans}}$</td>
<td>III-15 [ \frac{\sin \gamma_s}{\tan \alpha_s} ]</td>
</tr>
<tr>
<td>East-west</td>
<td>$\cos \theta$</td>
<td>III-16 [ \sqrt{1 - \cos^2 \alpha_s \sin^2 \gamma_s} ]</td>
</tr>
<tr>
<td></td>
<td>$\tan \theta_{\text{trans}}$</td>
<td>III-17 [ \frac{\cos \gamma_s}{\tan \alpha_s} ]</td>
</tr>
</tbody>
</table>

Graphics and formulas taken from:
Available online soon: [www.dlr.de/enermena](http://www.dlr.de/enermena)
Performance of LFC

- Optical Efficiency
- Incidence Angle Modifier
- Heat losses/ efficiency
- Dependency on season
- Comparison with Parabolic Trough
Performance of LFC
> Efficiency of a line focus system (LFC and PTC)

- Peak optical efficiency
- Correction by current sun position
  - PTC: incident angle
  - LFC: incident & transversal angle
- Correction by other external effects (e.g. cleanliness)
- Correction by heat loss
Performance of LFC > Optical efficiency

- Peak efficiency lower than for parabolic troughs due to
  - Astigmatism (mirrors on horizontal plane cannot reach ideal parabola)
  - Shading by receiver
  - Projected mirror surface
- At low sun position:
  - Shading
  - Blocking
  - Cosine losses
Performance of LFC > Incidence Angle Modifier

- Incidence Angle Modifier (IAM)
- IAM = IAM$_{long}$ * IAM$_{trans}$
- Longitudinal IAM usually function of incidence angle (not longitudinal angle): IAM$_{long}$ = f($\theta_i$)
- Usually derived from ray-tracing
- Includes cosine, spillage, shading, blocking etc.
Performance of LFC > Incidence Angle Modifier

→ Longitudinal IAM similar for Parabolic trough and Linear Fresnel
→ For Fresnel additional component due to transversal effects
Performance of LFC > Heat Losses

- Heat loss correlation usually given in [W/m]
- Receiver characteristic, independent from collector
- Recommended for vacuum receivers:
  \[ q_{loss} = c_1 T_{abs} + c_4 T_{abs}^4 \]
- For low temperature and non-vacuum \( T^3 \) sufficient
Performance of LFC > Efficiency from Heat Loss

- Take coefficients from heat loss curve \((c_1, c_4)\)
- Correct by DNI (or beam irradiance \(G_b\)) and aperture width \(w_{ap}\)
- For high temperatures
  - Use correction with \(T^4\) [\(T\) in °C] or at least \(T^3\)
  - Use absorber temperature [1]
- DNI also has an effect on heat losses! See e.g. [2]

As a rule of thumb:

\[
\eta_{\text{therm,coll}} = \eta_{\text{opt}} - \eta_{\text{HL}} = \eta_{\text{opt}} - \frac{1}{DNI \cdot w_{ap}} \left( c_1 \cdot T_{abs} + c_4 \cdot T^4 \right)
\]

\[
T = 100\ldots600^\circ\text{C}:
\]

\[
\eta_{\text{therm,coll}} = \eta_{\text{opt}} - \frac{a_1}{w_{ap}} \cdot \frac{(T_{\text{fluid}} - T_{\text{amb}})}{DNI} - \frac{a_2}{w_{ap}} DNI \cdot \left( \frac{(T_{\text{fluid}} - T_{\text{amb}})}{DNI} \right)^2
\]

\[
T = 100\ldots400^\circ\text{C}:
\]


Performance of LFC > Annual Yield Modeling

- Analog to parabolic trough plants, only considering different IAM
- Repeat for various years and “typical meteorological year”, since highly dependent on DNI distribution and location
- see latest activities of guiSmo project for more details: http://www.solarpaces.org/Tasks/Task1/modelingguidelines.htm
- Some selected studies:
Comparison with PTC > Optical performance

- Scaled EuroTrough PTC vs. Novatec LFC
- Both with vacuum absorber

→ Optical performance of Fresnel lower especially at low sun angles
Comparison with PTC > Optical performance

- Include optics in site characterization for line focus systems
Comparison with PTC > Optical power input

- Fresnel shows summer peak, while PTC shows broader plateau
Comparison with PTC > Overall performance

\[ \eta_{\text{therm}} \] vs. 

<table>
<thead>
<tr>
<th>temperature difference [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT 850 W/m²</td>
</tr>
<tr>
<td>PT 500 W/m²</td>
</tr>
<tr>
<td>LF 850 W/m²</td>
</tr>
<tr>
<td>LF 500 W/m²</td>
</tr>
</tbody>
</table>
Comparison with PTC > Overall performance

- **Question of the day**
  - Why is the relative decrease in performance at low DNI values smaller for LFC than for PTC?

- **Answer:**
  - Higher concentration ratio of LFC due to larger aperture width and same receiver → more heat input per receiver length → thus heat loss relatively lower.
Comparison with PTC > Annual performance

Assumptions:
- All configurations produce 220 GWh/year at site Daggett
- Storage size 12 full load hours
- HTF is solar salt
- Variation in solar field costs (€/m²) while keeping power block and storage costs constant

→ Worse performance of LF is to be compensated by lower specific costs

Components of LFC

- Mirrors and Collectors
- Receiver Concepts
LFC Collectors > Novatec Solar

Source: Novatec Solar
LFC Collectors > Areva Solar

Source: Areva Solar
LFC Collectors > Areva Solar (Kimberlina)

Source: Areva Solar
LFC Collectors > Areva Solar

Source: Areva Solar
LFC Collectors > Solar Power Group

Source: SPG, Ferrostaal, DLR
LFC Collectors > Solar Power Group

Source: SPG, Ferrostaal, DLR
LFC Collectors > Solar Euromed

Source: Solar Euromed
# LFC Collectors > Selected Commercial LFCs

<table>
<thead>
<tr>
<th></th>
<th>Novatec Nova 1</th>
<th>SPG Fresdemo</th>
<th>SPG Type 3</th>
<th>Mirroxx LF</th>
<th>Areva Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module length [m]</td>
<td>44.8</td>
<td>100</td>
<td>96</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Module aperture width [m]</td>
<td>16.56</td>
<td>21.25</td>
<td>22</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>Focal length [m]</td>
<td>7.4</td>
<td>8.25</td>
<td>8.8</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Module net area [m²]</td>
<td>513.6</td>
<td>1432.3</td>
<td>1467.8</td>
<td>351.0</td>
<td></td>
</tr>
</tbody>
</table>
LFC Receivers > Non-evacuated tube + secondary

- Receiver tube with selective coating
- Insulated secondary mirror
- Glass cover to reduce heat losses
- e.g. Nova-1, SPG/Fresdemo
LFC Receivers > Non-evacuated tube + secondary
LFC Receivers > Non-evacuated tube + secondary
LFC Receivers > Non-evacuated tube + secondary
LFC Receivers > Evacuated tube + secondary

- Conventional vacuum type receiver as in parabolic troughs
- Adapted secondary mirror configuration
- No glass cover
- Optical efficiency slightly lower than with non-evacuated tube
- e.g. Supernova (and Industrial Solar)

Source: Novatec Solar, SolarPACES 2011
LFC Receivers > Cavity with parallel tubes

- Multiple small diameter receiver tubes in focal line
- Insulated trapezoidal cavity
- No secondary reflector
- Glass cover to reduce heat losses
- e.g. Areva Solar

LFC Receivers > Cavity with parallel tubes

LFC Length Compensation > Areva Solar

Sources: Areva Solar;
LFC Construction (Areva Solar)
## Power Plants in Operation

<table>
<thead>
<tr>
<th></th>
<th>Solar-mundo</th>
<th>Fresdemo</th>
<th>Liddell</th>
<th>PE-1</th>
<th>Augustin Fresnel 1</th>
<th>PE-2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LFC Company</strong></td>
<td>Solarmundo</td>
<td>Ferrostaal/SPG</td>
<td>Ausra</td>
<td>Novatec Solar</td>
<td>Solar Euromed</td>
<td>Novatec Solar</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>Liège, Belgium</td>
<td>PSA, Spain</td>
<td>Liddell, Australia</td>
<td>Calasparra, Spain</td>
<td>Themis platform, France</td>
<td>Calasparra, Spain</td>
</tr>
<tr>
<td><strong>Total area</strong></td>
<td>2,400 m²</td>
<td>1,432 m²</td>
<td>18,490 m²</td>
<td>21,571 m²</td>
<td>302,000 m²</td>
<td></td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td>100m, up to 450°C</td>
<td>Preheating</td>
<td>Sat. steam 50 bars, 1.4 MWe</td>
<td>Sat. steam 55 bars, 30 MWe</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
LFC Test Plants

Solarmundo Plant, Belgium

SPG/Ferrostaal: FresDemo, PSA, Spain
LFC Test Plants

Areva Solar (Ausra), Liddell, Australia

Solar Euromed, Augustin Fresnel 1, France
Commercial LFC Plants

Novatec Solar, PE-1, Calasparra, Spain

Novatec Solar, PE-2, Calasparra, Spain
LFC Plant Outlook

- Novatec Solar:
  - Under construction: Liddell (co-firing to coal plant)
    9.3 MWth, 4x403m loop length, 18’490 m²,
    saturated steam at 55 bar/ 270°C

- Areva Solar:
  - Kimberlina, CA, USA: 25 MWth, 5 MWe
    (still under construction?)
LFC Suppliers for Process Heat
An incomplete list...

- Chromasun, Australia
- Industrial Solar (former Mirroxx), Germany
- Soltigua, Italy
- Elianto, Italy
- Cnim, France
- …

Source: Industrial Solar
LFC Developments > Overview

- Use economies of scale
  - Increase degree of automation in production, construction and maintenance
  - Optimize collector design
- Develop receivers for high temperatures
  - Vacuum tube with secondary
  - High temperature coating to become stable at air
  - Secondary reflector to remain stable at high temperatures
- Increase plant portfolio
  - Direct Steam Generation with superheating and at higher pressures
  - Optimized integration of DSG in fossil plants (ISCCS, booster…)
  - Molten salt plants
LFC Developments > Plants with DSG

- **Advantages**
  - Expensive ball joints can be avoided
  - Main heating from below to enhance boiling and avoid critical temperature differences around circumference
  - All commercial LFC plants use DSG so far
  - Easy integration in fossil plants (ISCCS, booster…)

- **Disadvantages**
  - No long term storage commercially available (yet)
LFC Developments > Plants with Molten Salt
LFC Developments > Plants with Molten Salt

- Advantages
  - Flexible joints can be avoided
  - Easier anti-freeze and drainage operation due to less u-bends
  - Easier impedance heating

- Disadvantages
  - Shorter operation period leads to longer anti-freeze operation
  - Higher heat losses cause higher demand for anti-freeze (without vacuum receivers)
### LFC Developments > Comparison with PTC

<table>
<thead>
<tr>
<th>+</th>
<th>-</th>
<th>+</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>High optical efficiency</td>
<td>Flexible tube connections required</td>
<td>Low cost parts and mirrors</td>
<td>Low optical efficiency</td>
</tr>
<tr>
<td>Constant output</td>
<td>Wind loads/torque transfer</td>
<td>Low wind loads</td>
<td>Secondary reflector required (usually)</td>
</tr>
<tr>
<td>Few possibilities for cost-reduction</td>
<td></td>
<td></td>
<td>Less operation hours</td>
</tr>
</tbody>
</table>
LFC Developments > Fix Focus Trough

- Combine the best from both worlds:
  - Fix Focus
  - Constant effective aperture intraday
  - Focal line is center of mass
  - No secondary reflector

Source: DLR; Prahl, C., Schapitz, T., Uhlig, R.: SolarPACES 2011
LFC Developments > Fix Focus Trough

- Concept under development…

Source: DLR; Prahl, C., Schapitz, T., Uhlig, R.: SolarPACES 2011
Final remarks on LFC

Similar to parabolic trough, but…
- …fixed receiver pipe $\rightarrow$ no ball joints
- …trough shape “split” into multiple small mirror facets
- …lower optical performance
- …lower construction cost due to rapid assembly
- …lower susceptibility to wind damage
- …more efficient land use
- …light construction allowing small motors

Future success depending on costs and application…

Source: Novatec Solar
Questions and Discussion…

- Contact: jan.feldhoff@dlr.de