Linear Fresnel Collectors

A Technology Overview

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

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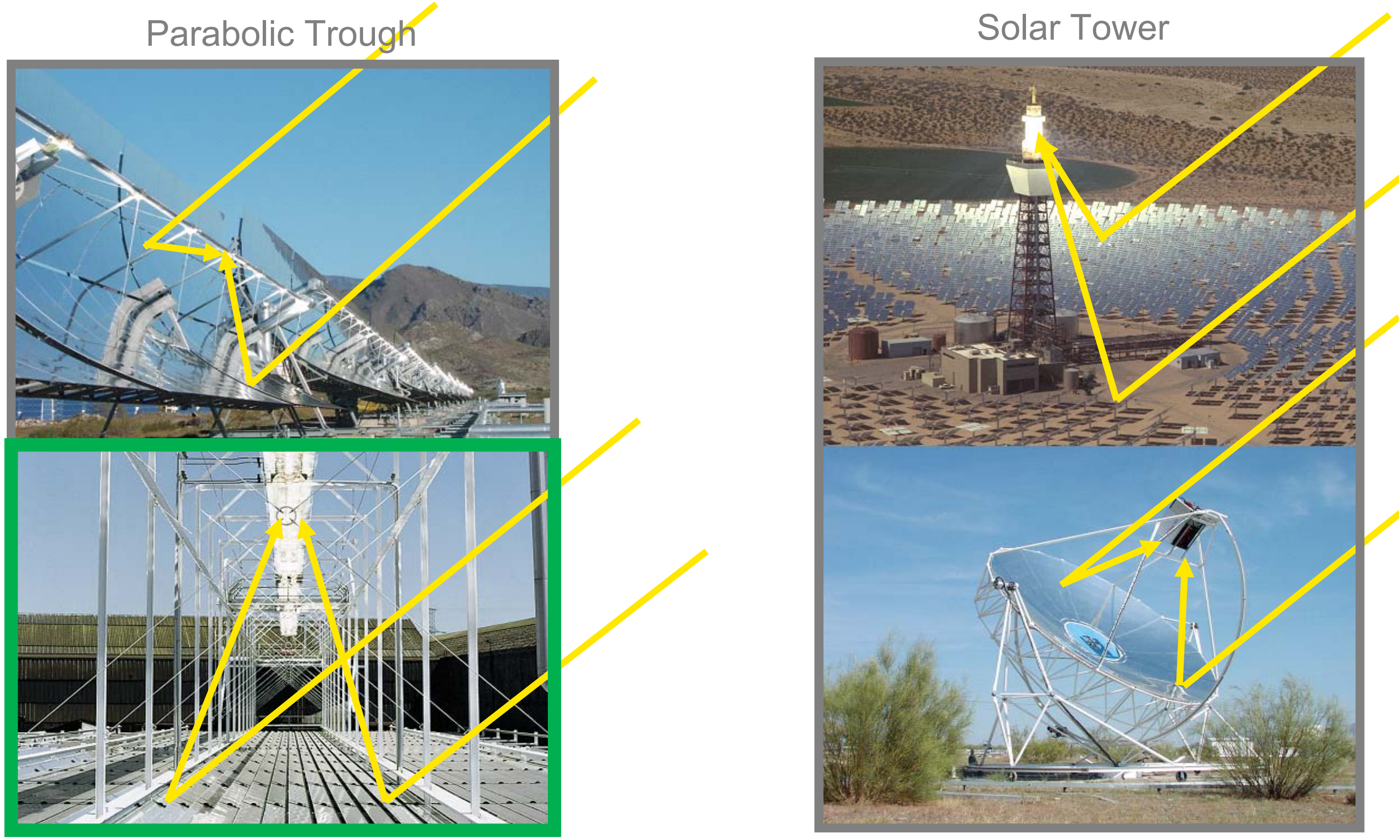
Overview of CSP Systems

Parabolic Trough

Solar Tower



Linear Fresnel

Dish-Stirling

Up to 550 °C, Steam Turbines

Up to 1000°C, Gas Turbines/Motors

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

Source: Novatec Solar

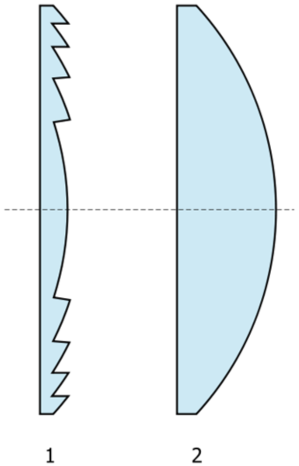
Overview

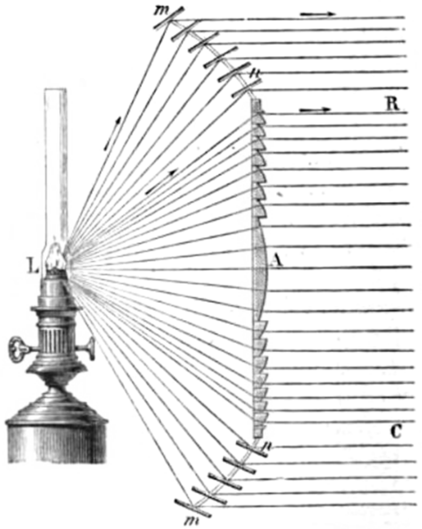
1. The Linear Fresnel Principle
2. Optical characteristics of Linear Fresnel Collectors (LFC)
3. Performance characteristics of LFCs
4. Components of LFCs
5. Overview existing LFC Plants
6. Outlook on LFC Developments
7. Final Remarks

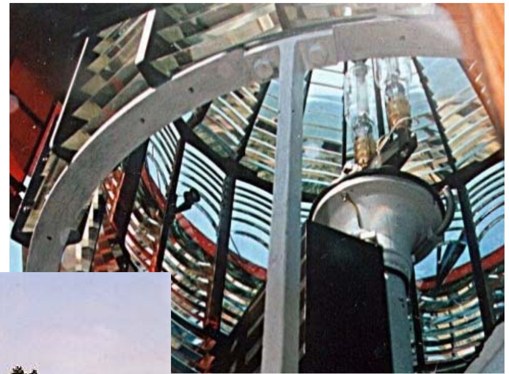
Source: DLR

Fresnel Principle

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

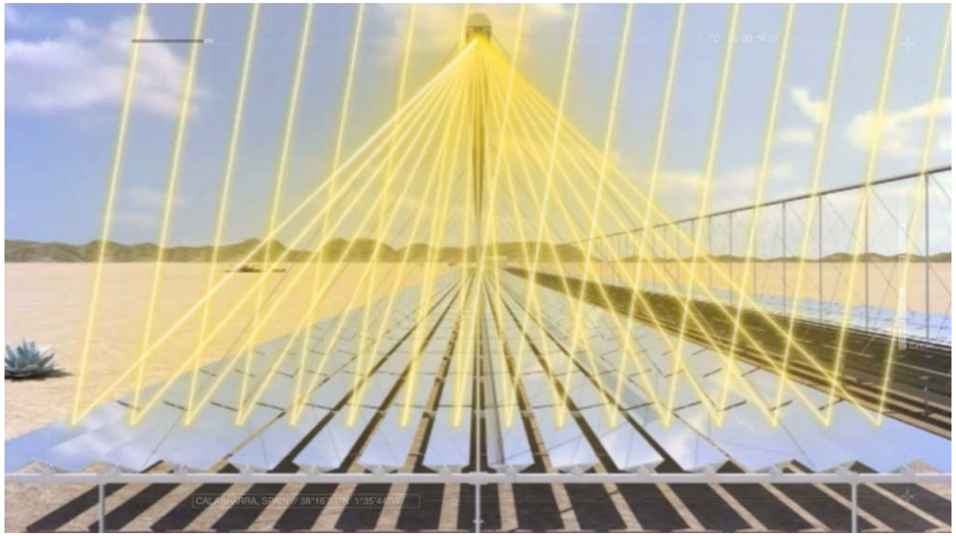


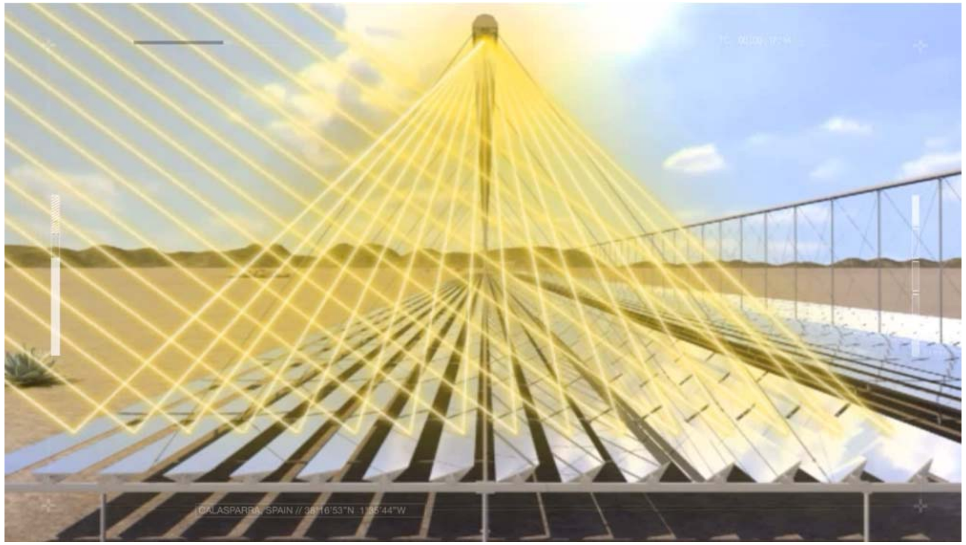




Pictures: Wikipedia

Fresnel Principle > Linear Fresnel Collectors (LFC)

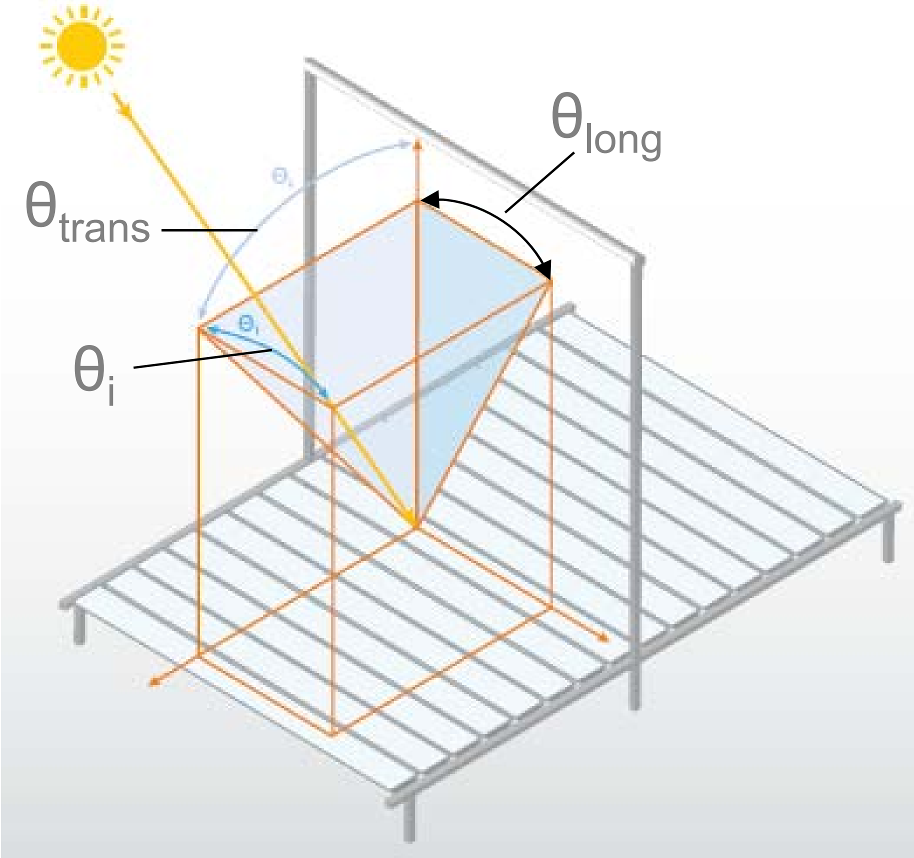




Source: Novatec Solar:
http://www.novatecsolar.com/20-1-Nova-1.html

Optical Characteristics of LFC

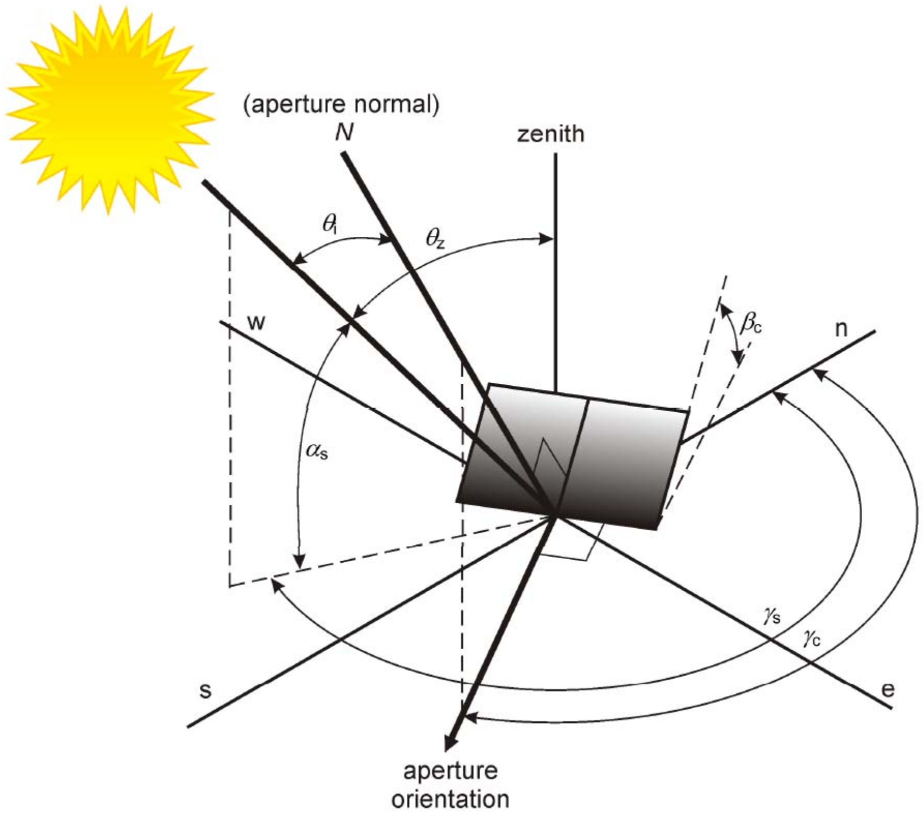
- Angle Definitions
- Calculation formula



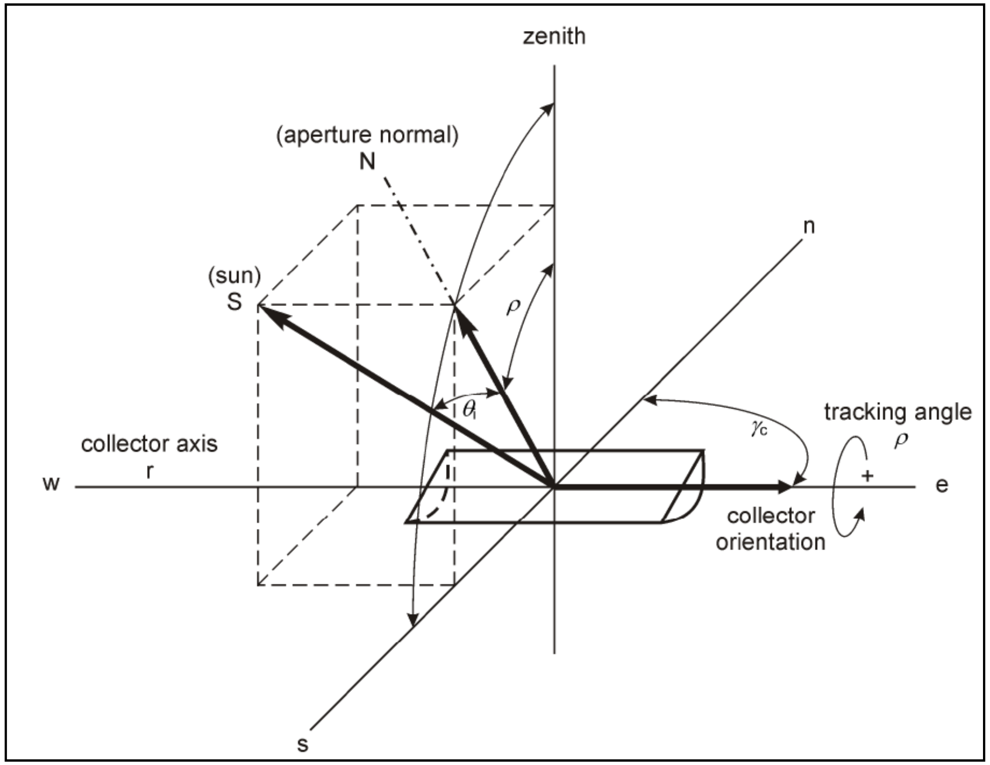
Solar Optics of LFC > Solar Angle Definitions

Solar azimuth	γ_s	°	The angle between North and the solar position projected on the horizontal plane; 0° ≤ α_s ≤ 360°
Solar elevation	α_s	°	Vertical angle between straight line to the sun and horizontal plane
Zenith angle	θ_z	°	Complementary angle to α_s; θ_z = 90° - α_s
Collector azimuth	γ_c	°	Angle between North and the aperture orientation
Collector axis tilt	β_c	°	Tilt angle between collector surface and horizontal plane; Usually 0 ≤ β_c ≤ 360
Angle of incidence	θ_i	°	Angle between straight line to the sun and collector normal

Declination	δ	°	Angle between sun beams and equatorial plane of the earth; Positive in summer (between end of march and end of September); -23.45° < δ < 23.45°.
Hour angle	ω	°	Angle between the meridian of the observer and the meridian parallel to the sunbeams; Negative in the morning; 0 on solar noon; -180° < ω < 180°
Geographic latitude	ϕ	°	Positive on the northern hemisphere; -90° < ϕ < 90°
Geographic longitude	λ	°	Positive eastward from Greenwich; -180° < λ < 180°



Solar Optics of Parabolic Trough Collectors



Solar azimuth	γ_s	°	The angle between North and the solar position projected on the horizontal plane; $0° \leq \alpha_s \leq 360°$
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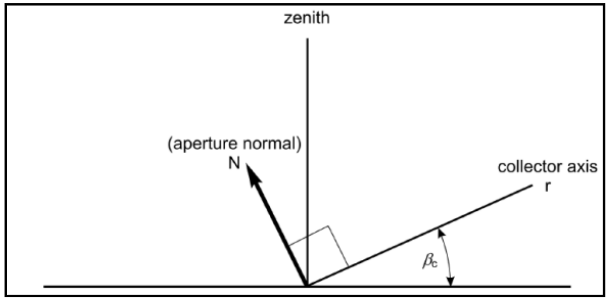
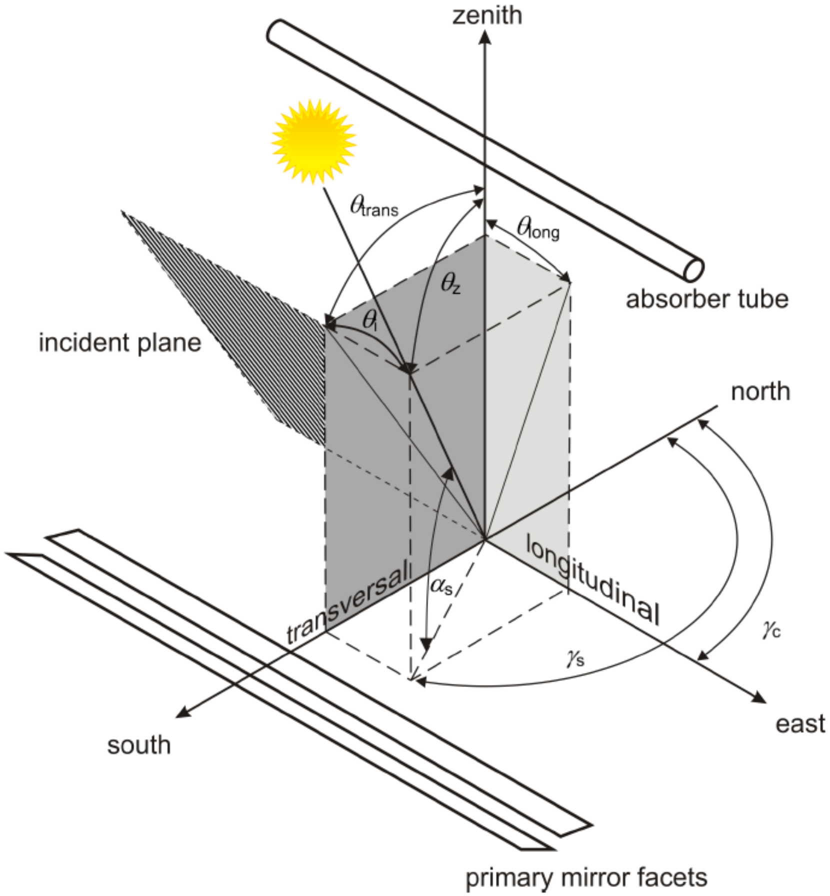


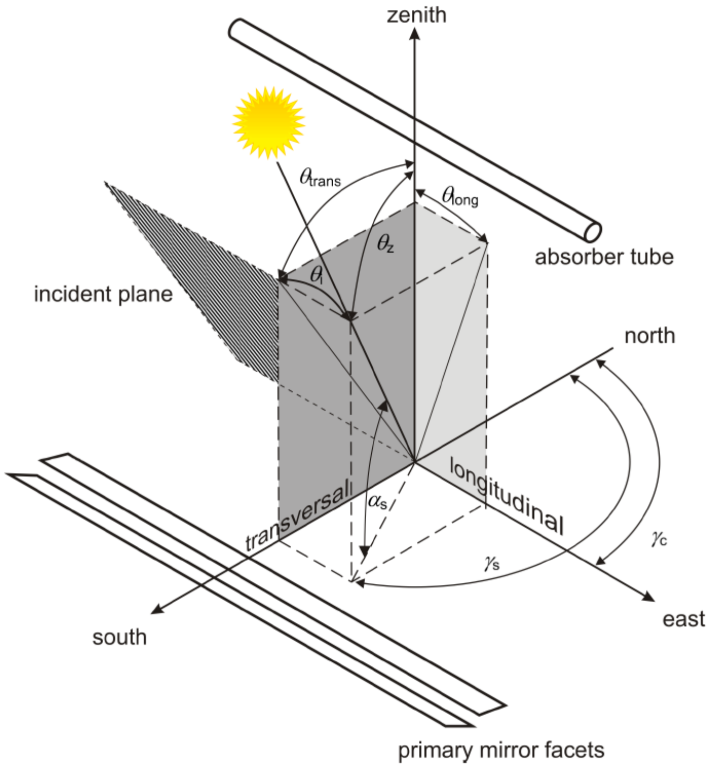
Solar Optics of LFC > Main Angles

Transversal angle	θ_{trans}	Angle between zenith and projection of straight line to the sun into the transversal plane
Longitudinal angle	θ_{long}	Angle between zenith and projection of straight line to the sun into the longitudinal plane
Incidence angle	θ_{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



Orientation	Angle	Further Description in enerMena report, section III.4.	
arbitrary	$\cos\theta_i$	III-12	$=\sqrt{1-\left(\cos(\alpha_s-\beta_c)-\cos\beta_c\cos\alpha_s[1-\cos(\gamma_s-\gamma_c)]\right)^2}$
	$\tan\theta_{trans}$	III-13	$=\cos\alpha_s\sin(\gamma_s-\gamma_c)/\left(\sin(\alpha_s-\beta_c)+\sin\beta\cos\alpha_s[1-\cos(\gamma_s-\gamma_c)]\right)$
North-south	$\cos\theta_i$	III-14	$=\sqrt{1-\cos^2\alpha_s\cos^2\gamma_s}$
	$\tan\theta_{trans}$	III-15	$=\sin\gamma_s/\tan\alpha_s$
East-west	$\cos\theta_i$	III-16	$=\sqrt{1-\cos^2\alpha_s\sin^2\gamma_s}$
	$\tan\theta_{trans}$	III-17	$=\cos\gamma_s/\tan\alpha_s$

Graphics and formulas taken from:
H. Schenk, M. Eck: YIELD ANALYSIS FOR PARABOLIC TROUGH SOLAR THERMAL POWER PLANTS – A BASIC APPROACH, enerMENA report, DLR Stuttgart, March 2012.
Available online soon: www.dlr.de/enermena

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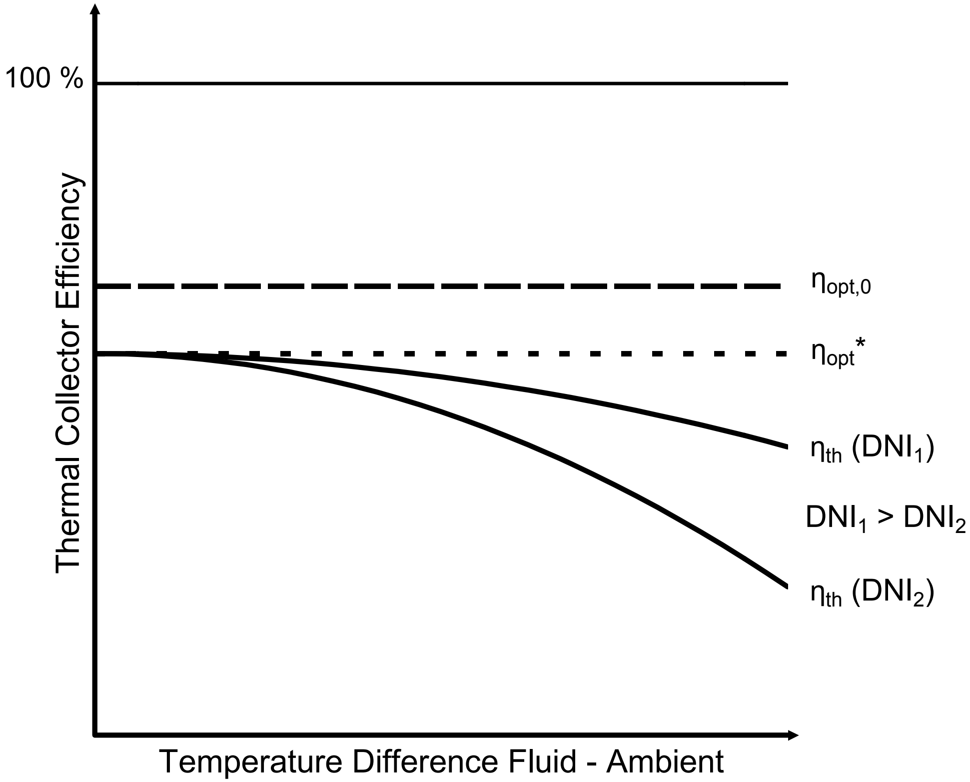
Performance of LFC

- Optical Efficiency
- Incidence Angle Modifier
- Heat losses/ efficiency
- Dependency on season
- Comparison with Parabolic Trough

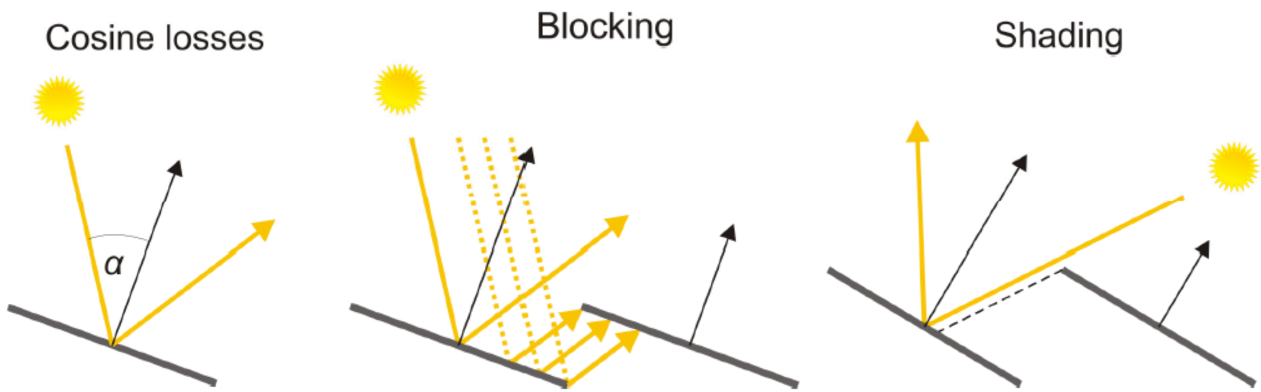
Performance of LFC
> Efficiency of a line focus system (LFC and PTC)



- 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



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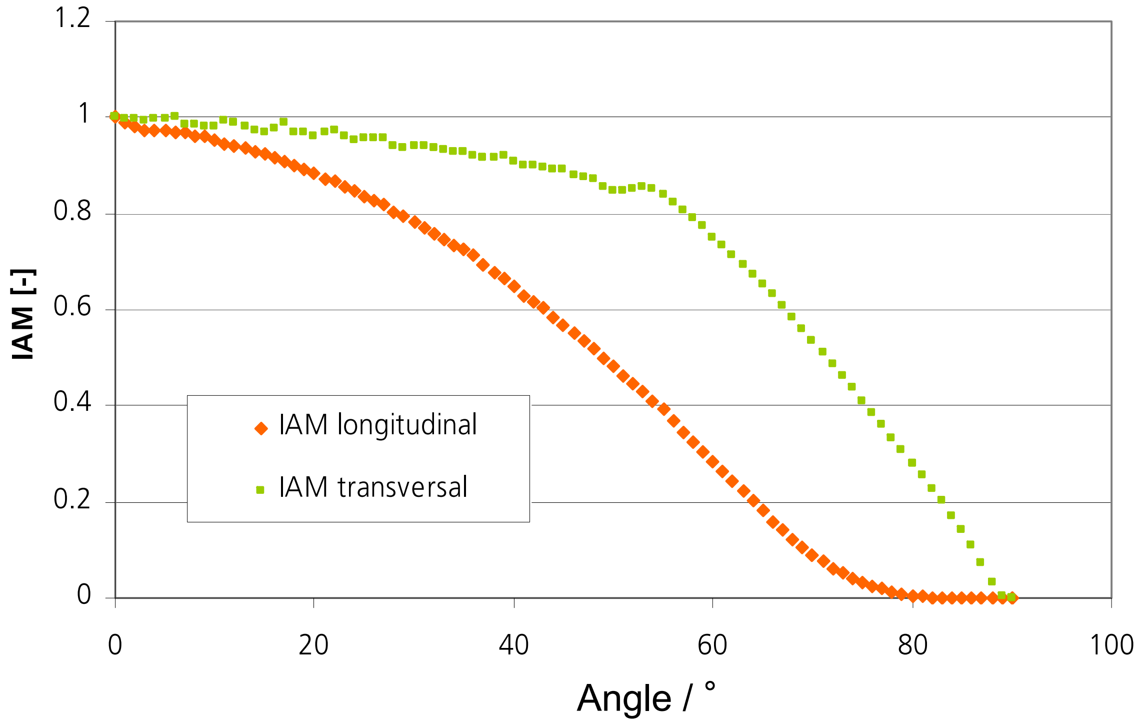
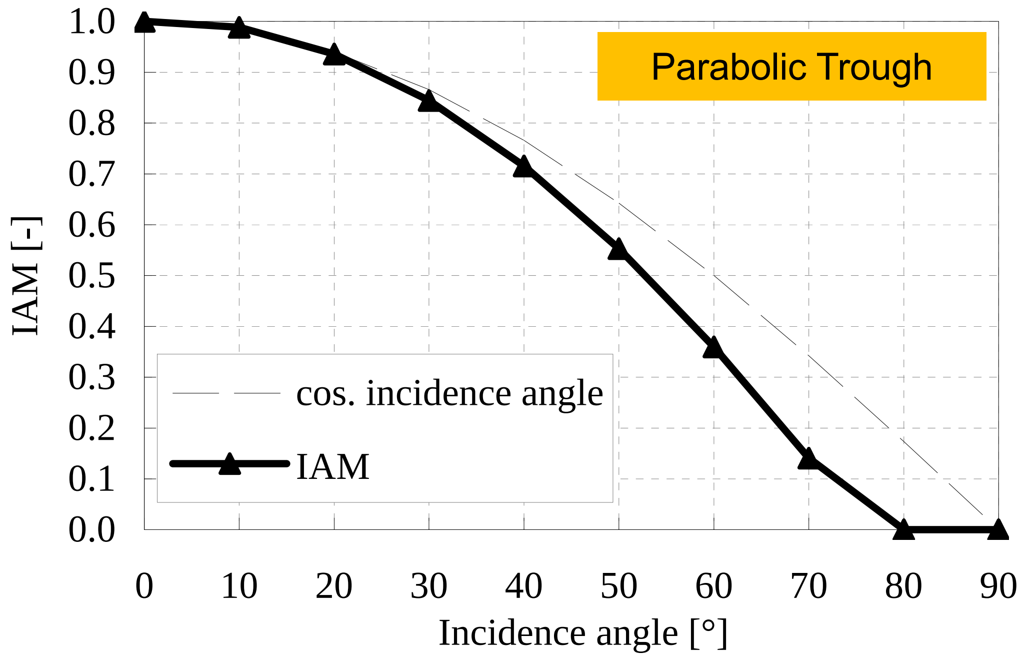
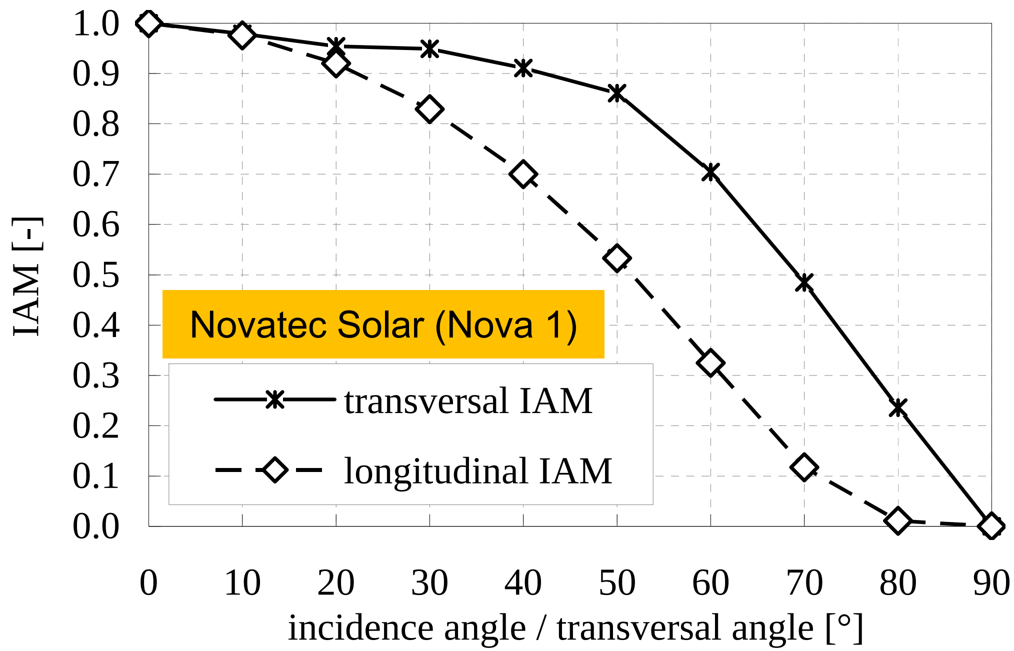
Performance of LFC > Incidence Angle Modifier

- 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

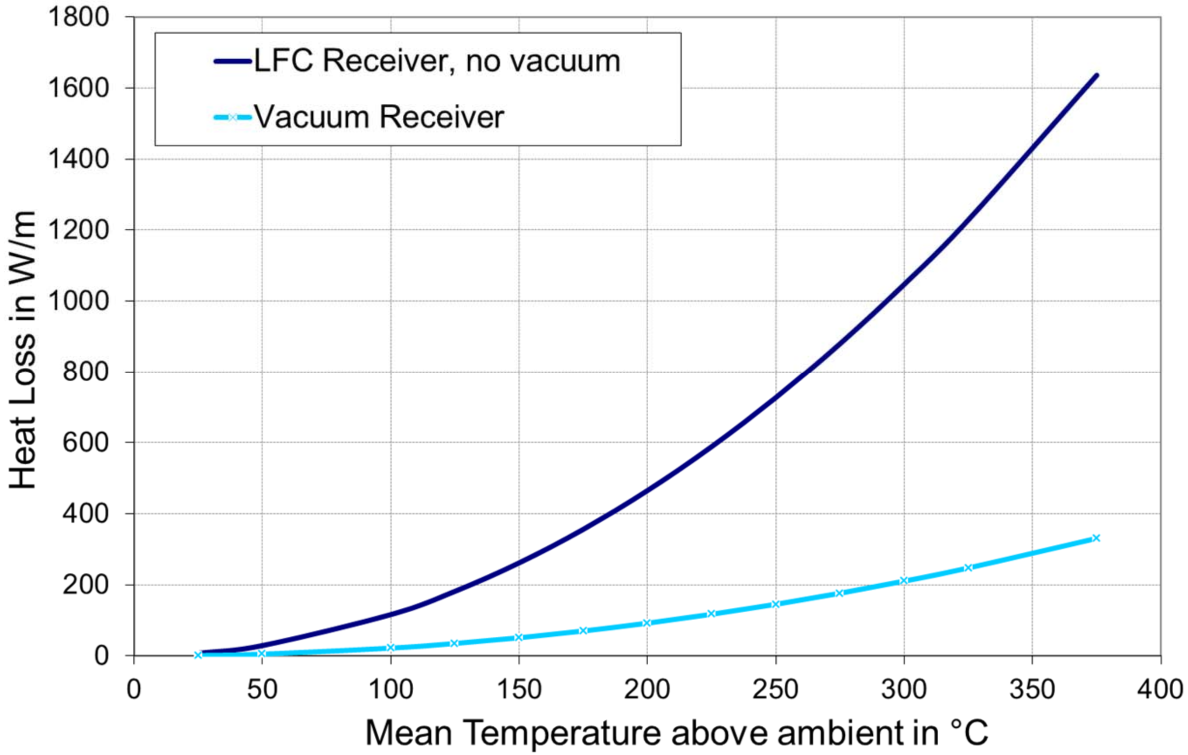
→ For Fresnel additional component due to transversal effects

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:

T = 100…600°C:

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

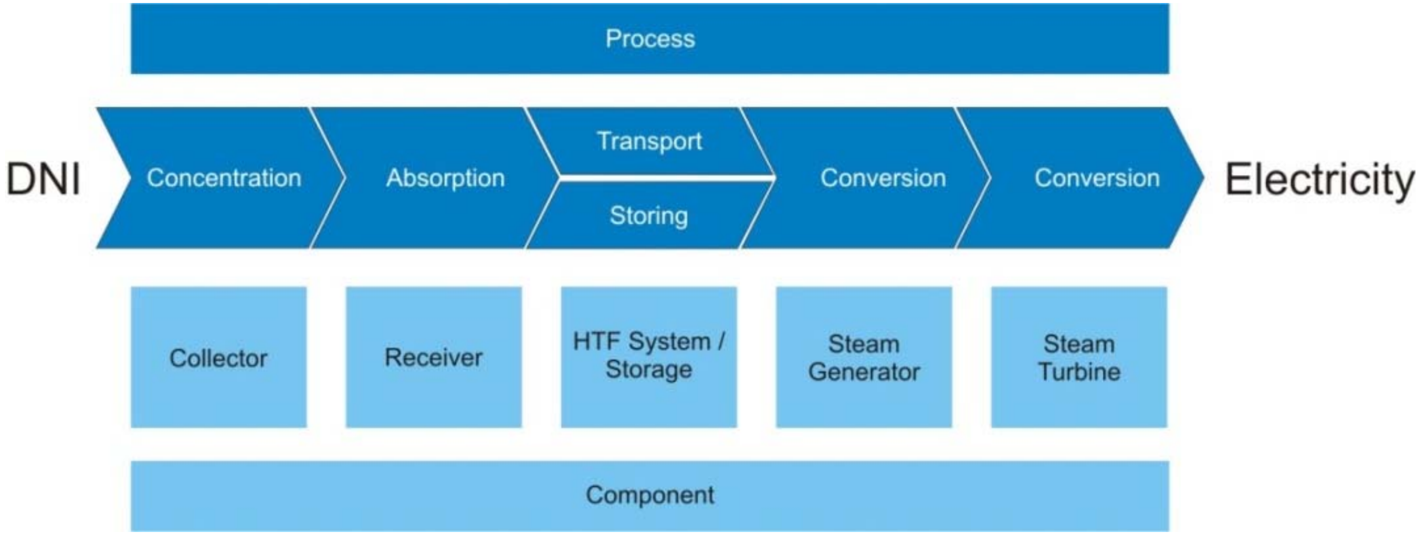
T = 100…400°C:

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

[1] Burkholder, F., and Kutscher, C., 2008, "Heat-Loss Testingof Solel'sUVAC3 Parabolic Trough Receiver," NREL/TP-550-42394
[2] Burkholder, F., and Kutscher, C., 2009, "Heat loss testing of Schott's 2008 PTR70 Parabolic Trough Receiver " NREL/TP-550-45633

Performance of LFC > Annual Yield Modeling

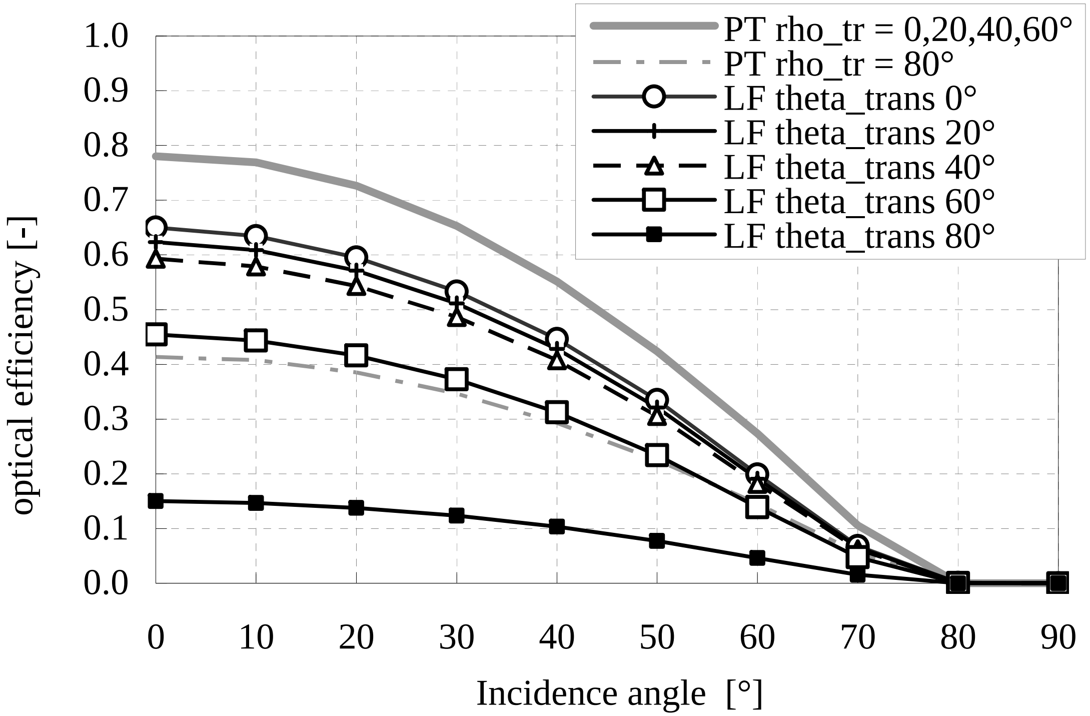
- Analog to parabolic trough plants, only considering different IAM
- Repeat for various years and “typical meteorological year”, since highly dependent on DNI distribution and location
- see latest activities of guiSmo project for more details: http://www.solarpaces.org/Tasks/Task1/modelingguidelines.htm



Comparison with PTC > Study Overview

- Some selected studies:
  - Dersch J., M. G., Eck M., Häberle A., 2009, "Comparison of linear Fresnel and parabolic trough collecor systems - system analysis to determine break-even costs of linear fresnel collectors," SolarPaces 2009, Berlin.
  - Morin, G., Dersch, J., Eck, M., et al., 2011, "Comparison of Linear Fresnel and Parabolic Trough Collector power plants," Solar Energy, pp. 12.
  - Giostri, A., Binotti, M., Silva, P., et al., 2011, "Comparison of two Linear Collectors in solar thermal Plants: Parabolic Trough vs. Fresnel," ASME 2011 5th International Conference on Energy Sustainability, Washington, DC, USA.
  - Schenk, H., Hirsch, T., Feldhoff, J.F., et al., 2012, “Energetic comparison of Linear Fresnel and Parabolic Trough Collector Systems,” ASME 2012 6th Int. Conference on Energy Sustainability, San Diego, CA, USA. (to be released in July 2012)

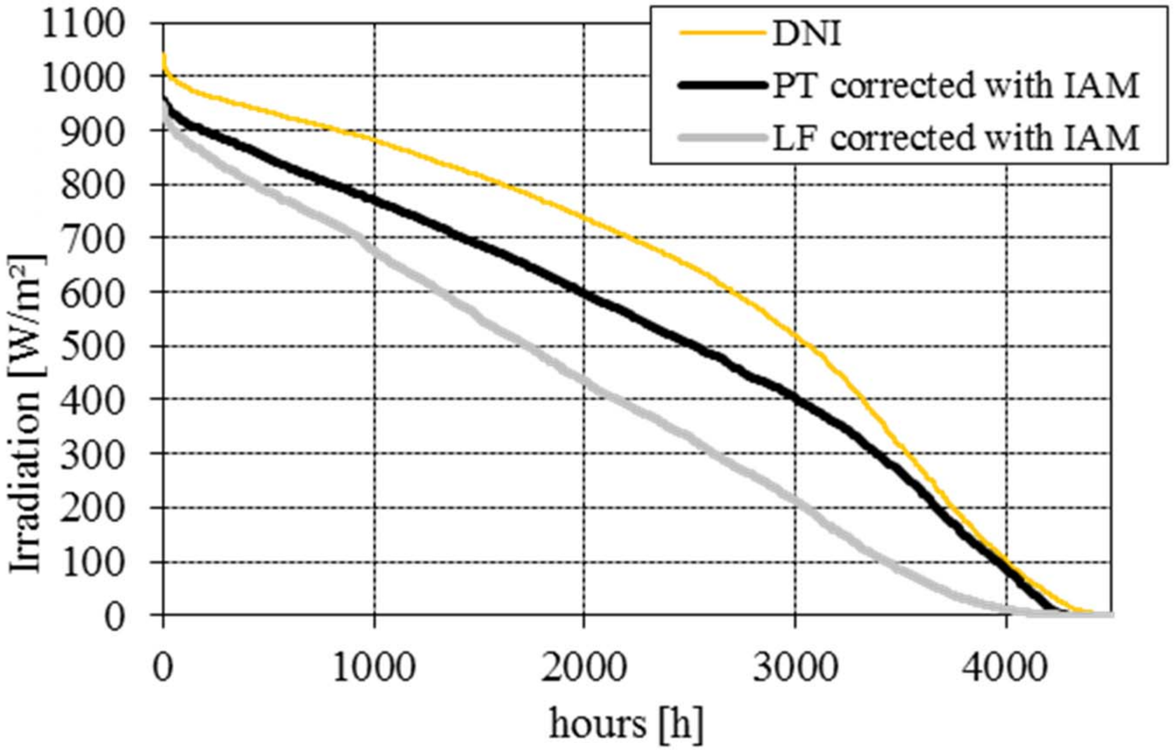
Comparison with PTC > Optical performance



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

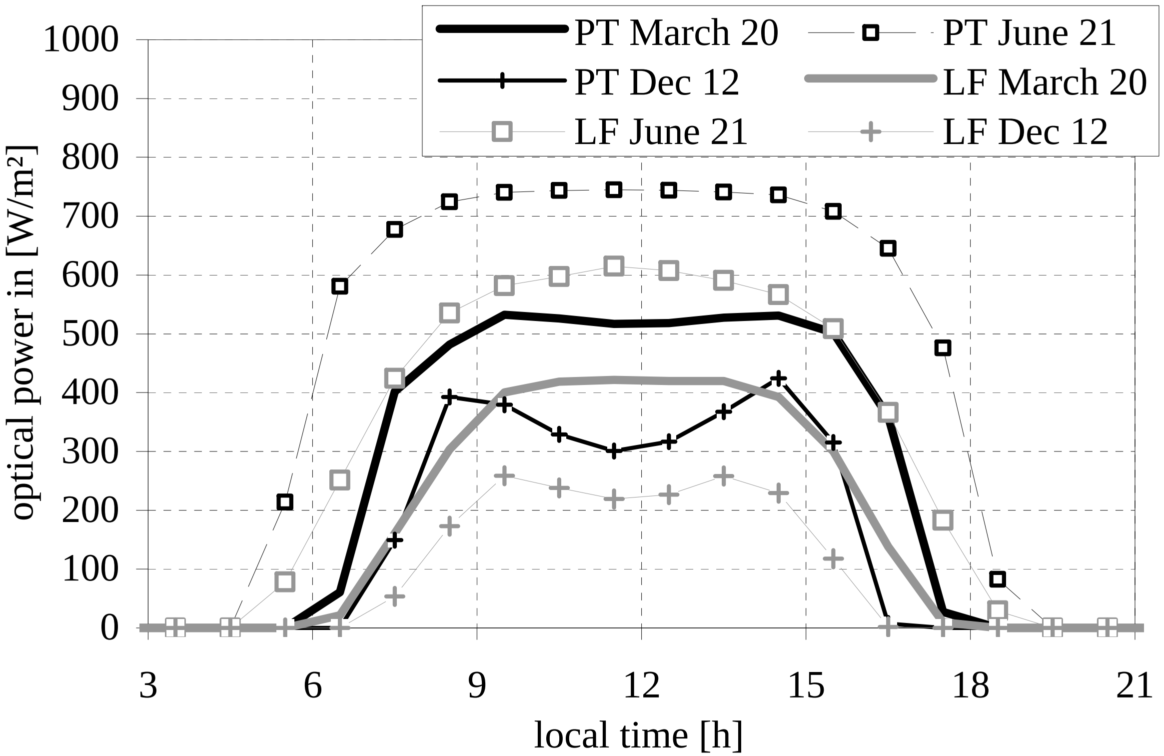
→ Optical performance of Fresnel lower especially at low sun angles

Comparison with PTC > Optical performance



- Include optics in site characterization for line focus systems

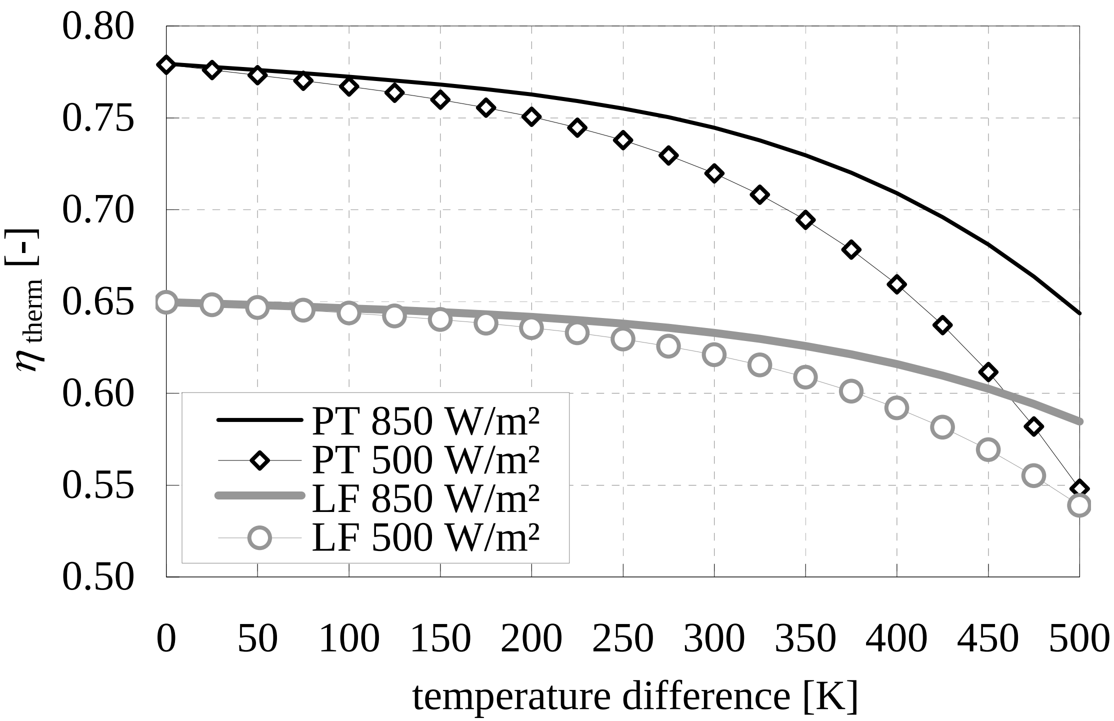
Comparison with PTC > Optical power input



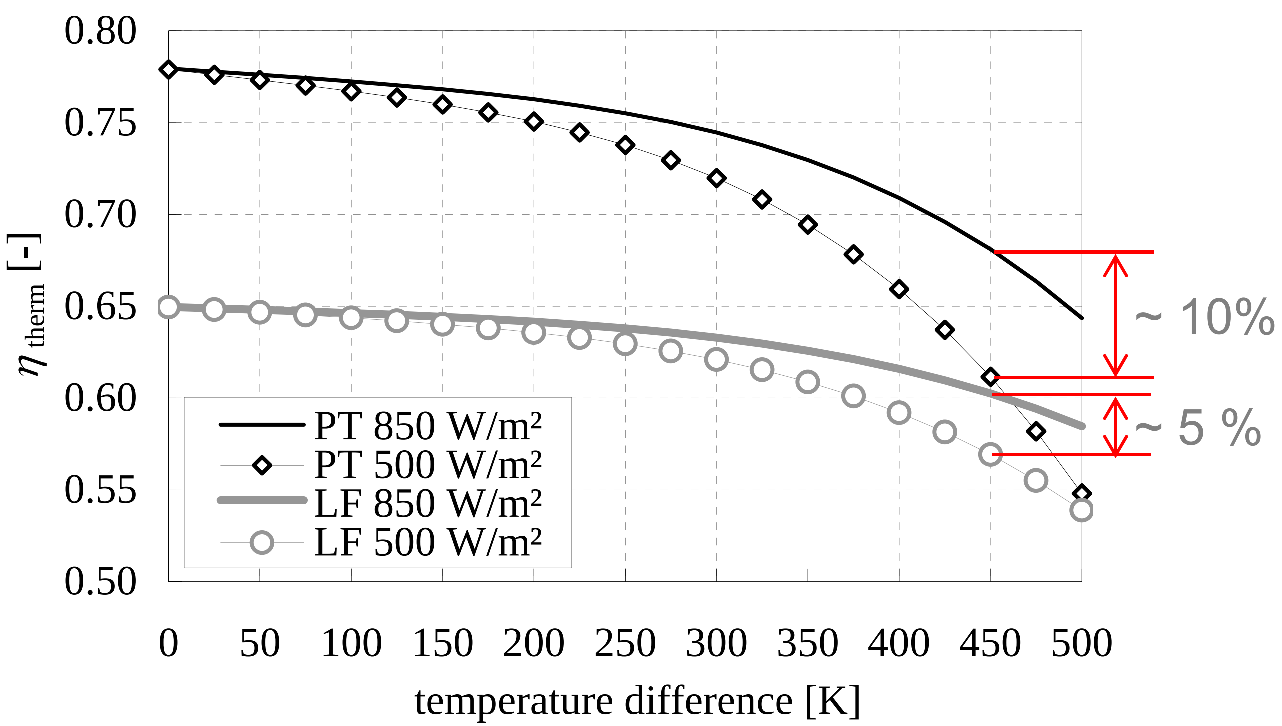
Location Daggett, USA

- Fresnel shows summer peak, while PTC shows broader plateau

Comparison with PTC > Overall performance

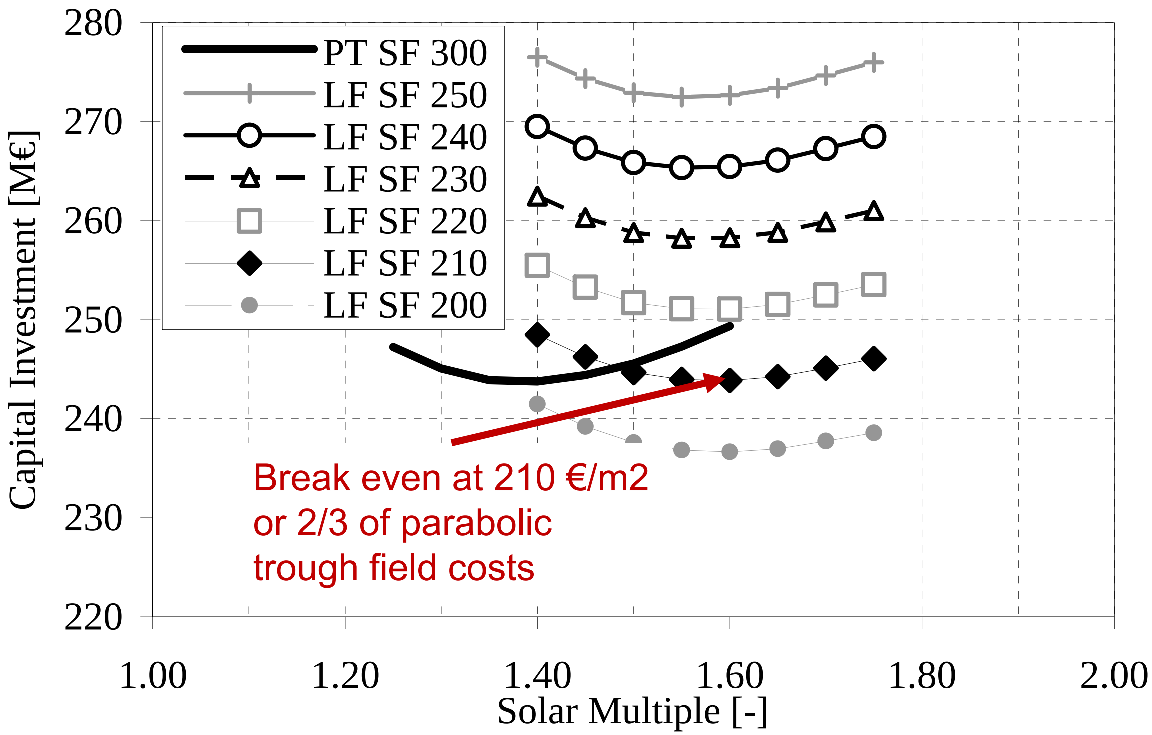


Comparison with PTC > Overall performance



- **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 (€/m^2) while keeping power block and storage costs constant

Schenk, H., Hirsch, T., Feldhoff, J.F., et al., 2012, "Energetic comparison of Linear Fresnel and Parabolic Trough Collector Systems," ASME 2012 6th Int. Conference on Energy Sustainability, San Diego, CA, USA. (to be released in July 2012)

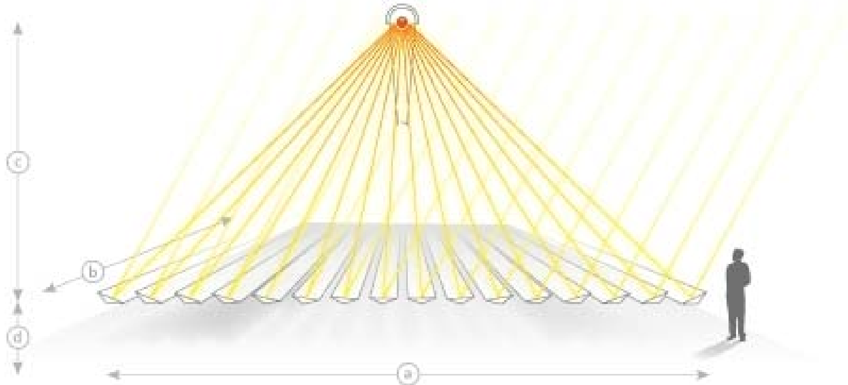
→ Worse performance of LF is to be compensated by lower specific costs

Components of LFC

- Mirrors and Collectors
- Receiver Concepts

Source: Novatec Solar

LFC Collectors > Novatec Solar



Source: Novatec Solar

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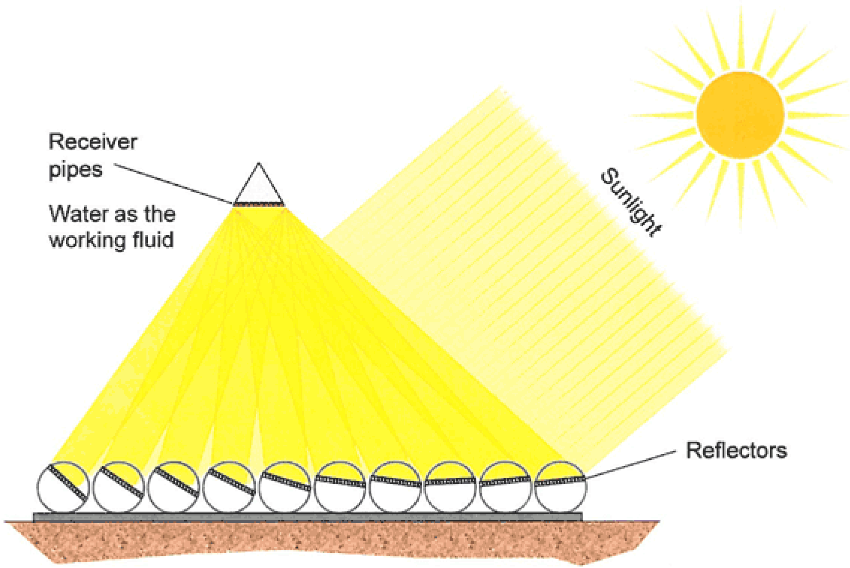
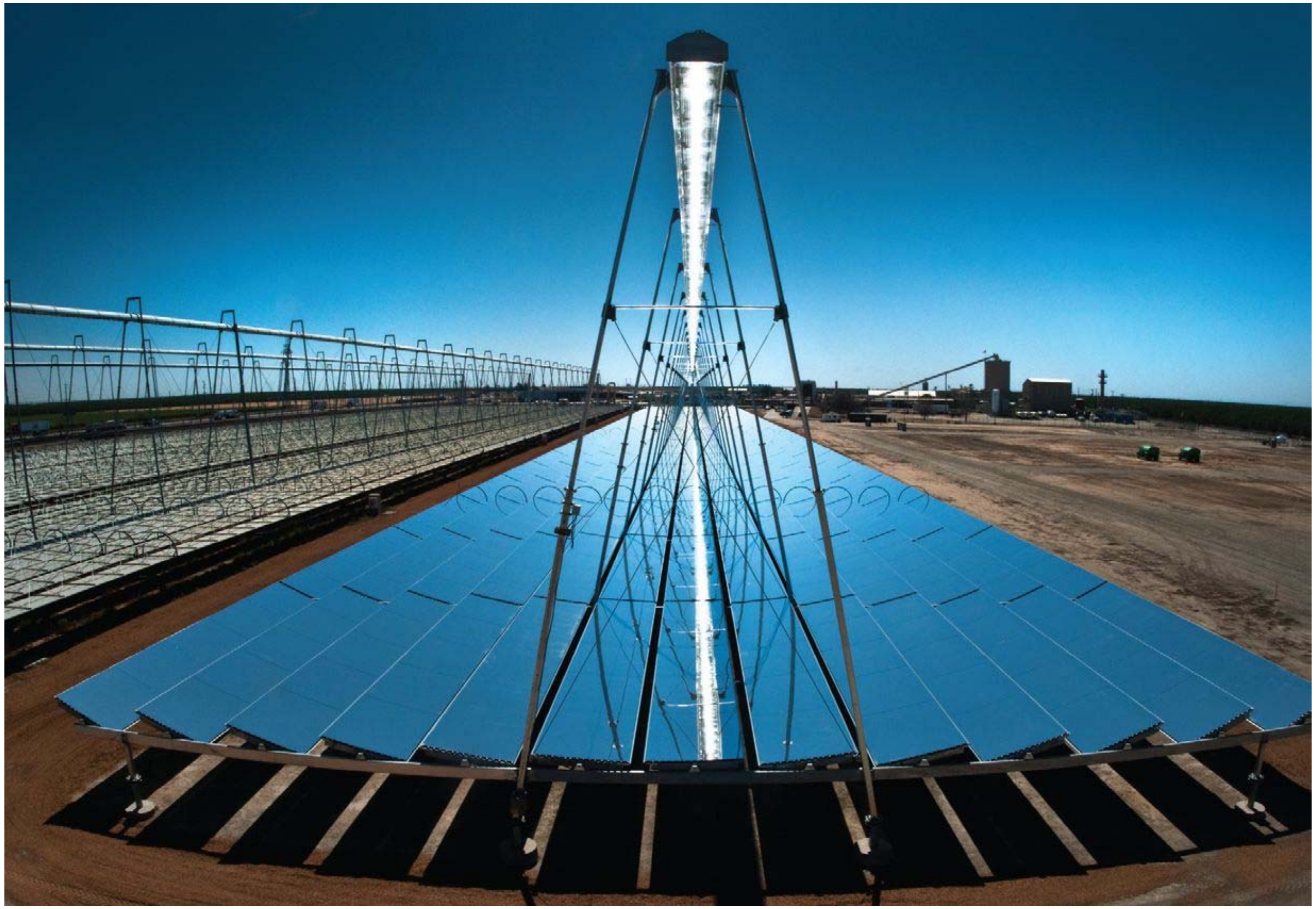
LFC Collectors > Areva Solar



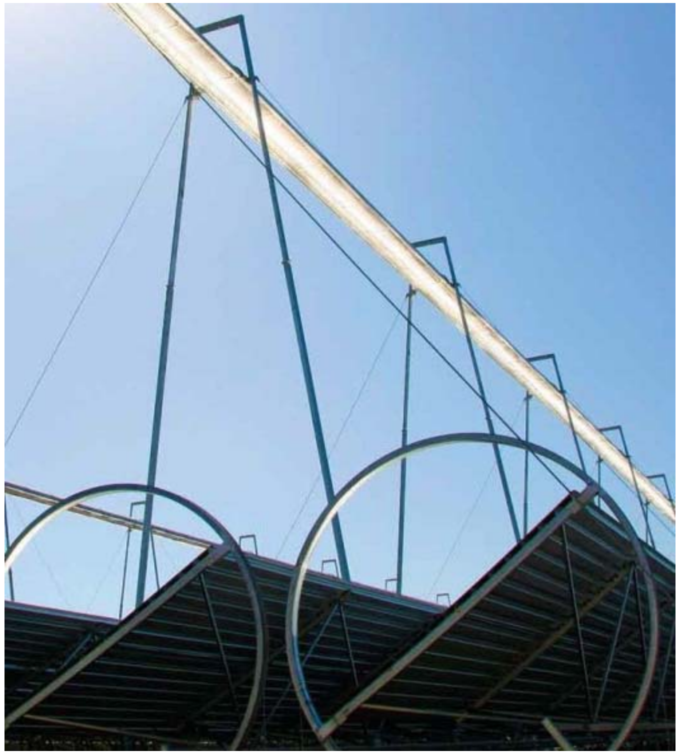
Source: Areva Solar

LFC Collectors > Areva Solar (Kimberlina)



Source: Areva Solar

LFC Collectors > Areva Solar



Source: Areva Solar

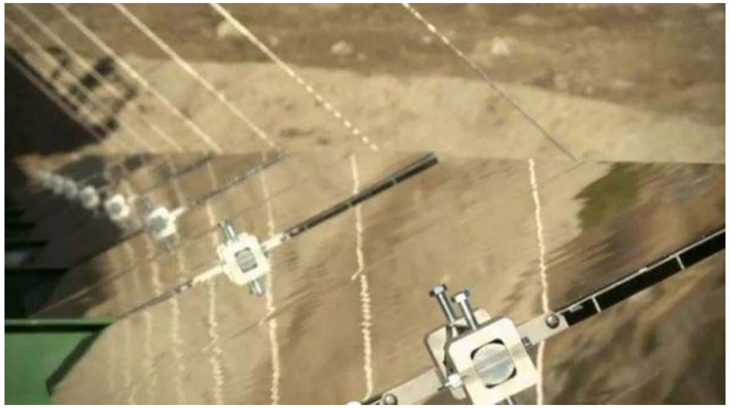
LFC Collectors > Solar Power Group

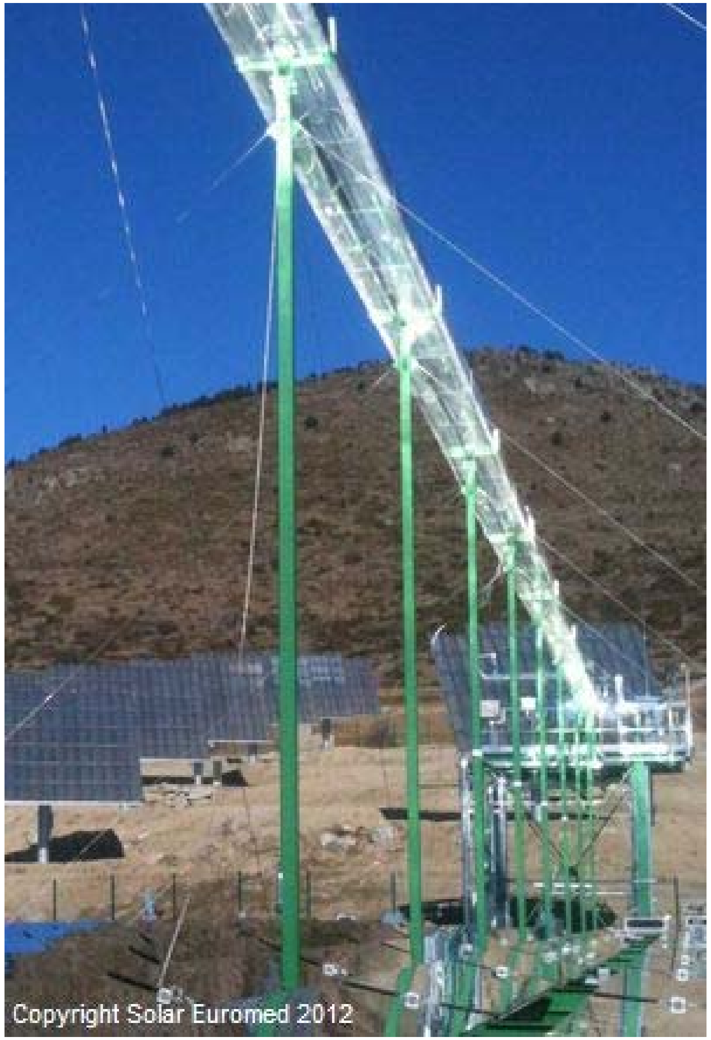
Source: SPG, Ferrostaal, DLR

LFC Collectors > Solar Power Group

Source: SPG, Ferrostaal, DLR

LFC Collectors > Solar Euromed





Source: Solar Euromed

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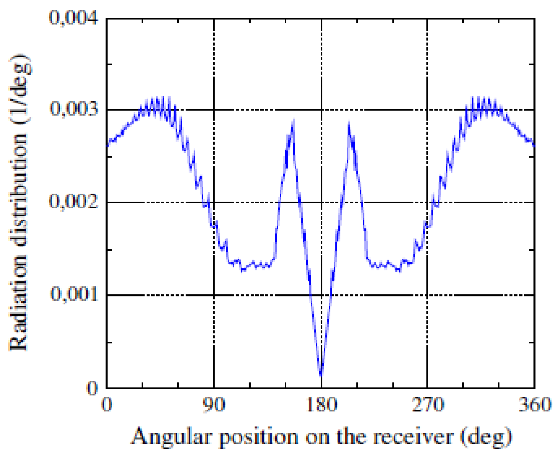
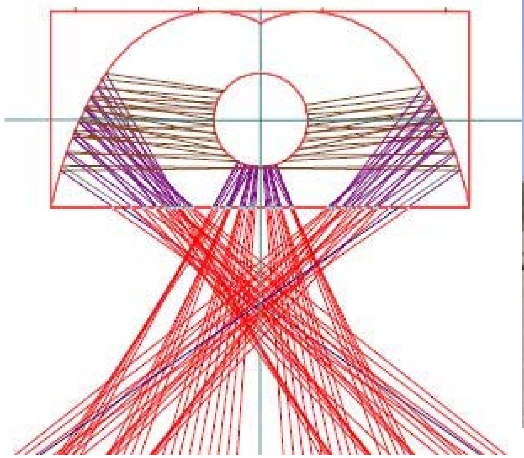
LFC Collectors > Selected Commercial LFCs

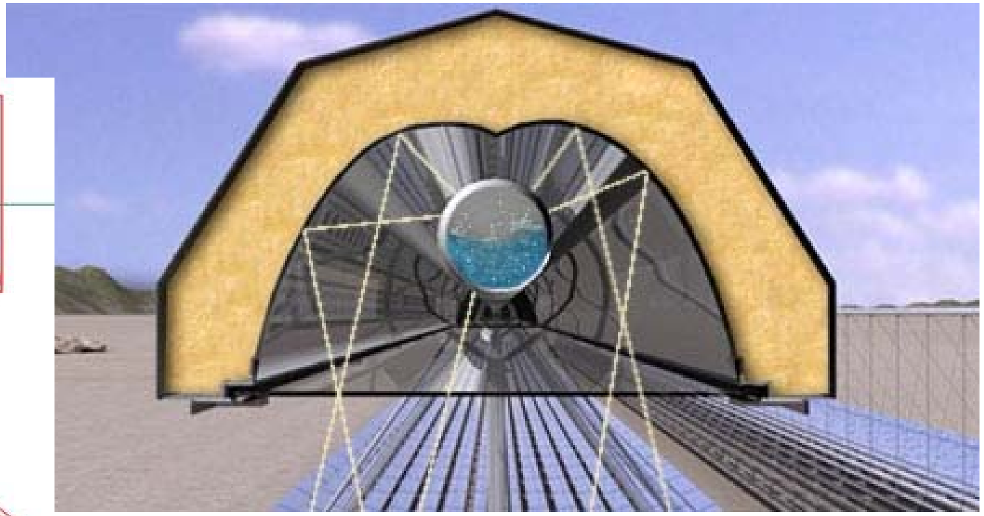
	Novatec Nova 1	SPG Fresdemo	SPG Type 3	Mirroxx LF	Areva Solar
Module length [m]	44.8	100	96	65	
Module aperture width [m]	16.56	21.25	22	7.5	
Focal length [m]	7.4	8.25	8.8	4	
Module net area [m²]	513.6	1432.3	1467.8	351.0	

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

Source: SPG

LFC Receivers > Non-evacuated tube + secondary

Source: SPG

LFC Receivers > Non-evacuated tube + secondary

Source: SPG, DLR

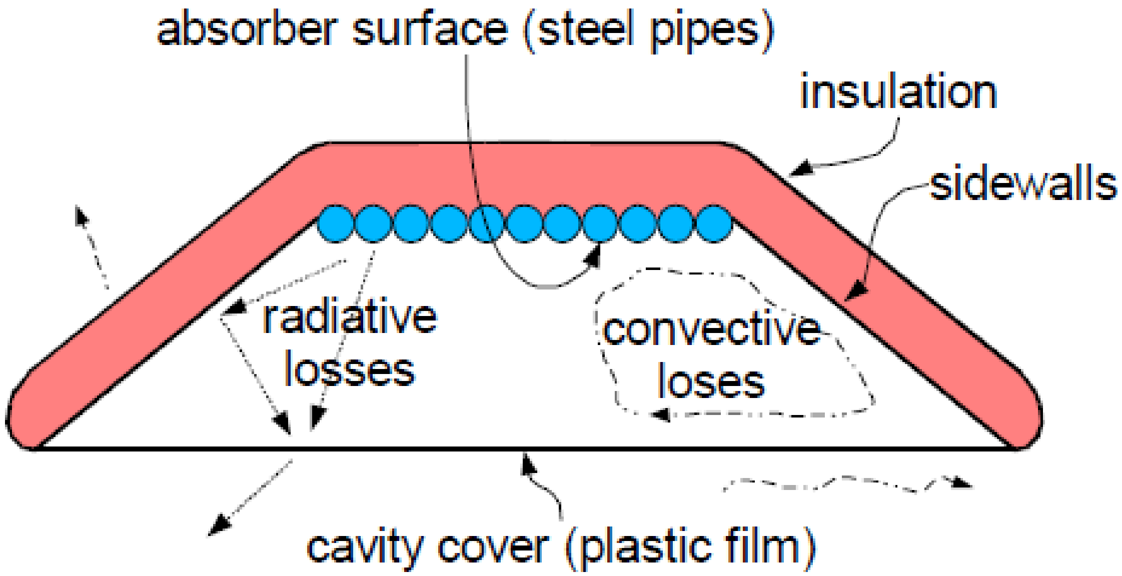
LFC Receivers > Evacuated tube + secondary

- 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

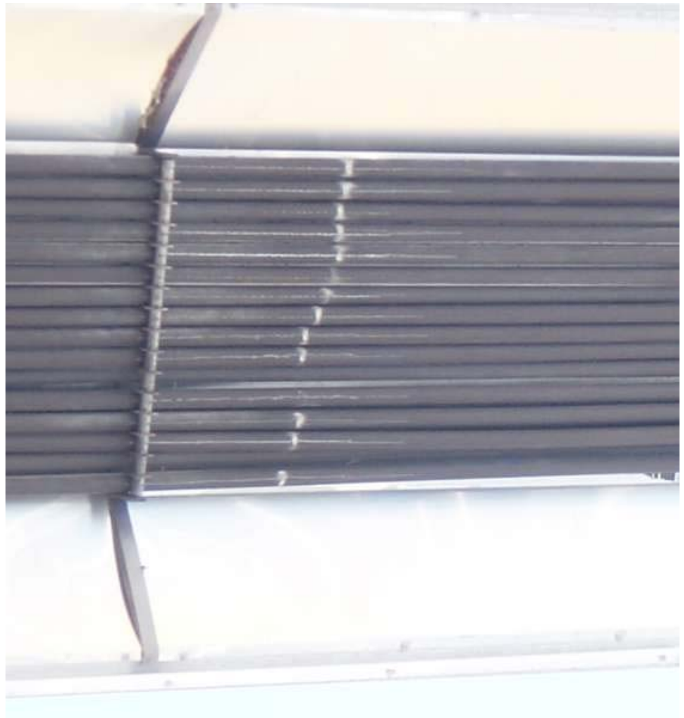
LFC Receivers > Cavity with parallel tubes

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



Pye, J. D., Morrison, G. L., and Behnia, M., 2003, "Transient Modelling of Cavity Receiver Heat Transfer for the Compact Linear Fresnel Reflector," ANZSES

LFC Receivers > Cavity with parallel tubes



Sources: Areva Solar;
Pye, J. D., Morrison, G. L., and Behnia, M., 2003, "Transient Modelling of Cavity Receiver Heat Transfer for the Compact Linear Fresnel Reflector," ANZSES

LFC Length Compensation > Areva Solar

Sources: Areva Solar;
Pye, J. D., Morrison, G. L., and Behnia, M., 2003, "Transient Modelling of Cavity Receiver Heat Transfer for the Compact Linear Fresnel Reflector," ANZSES

DLR

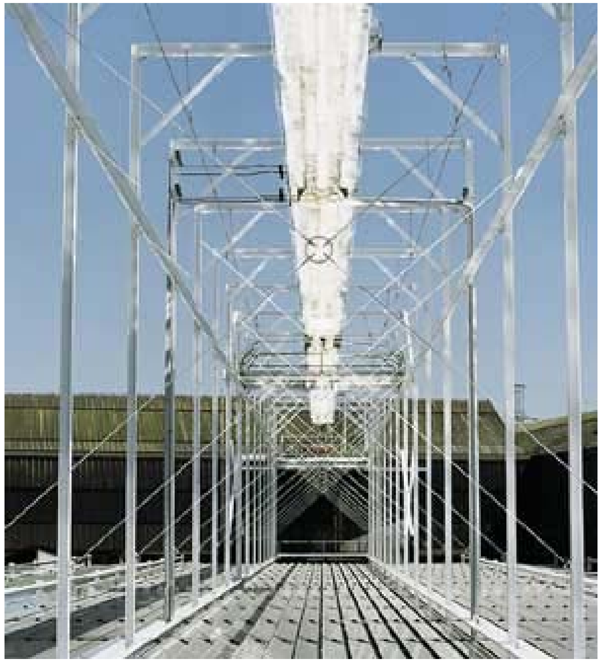
LFC Construction (Areva Solar)

Sources: Areva Solar;

Power Plants in Operation

	Solar-mundo	Fresdemo	Liddell	PE-1	Augustin Fresnel 1	PE-2
Year	1998	2007	2008	2009	2009	2012
LFC Company	Solarmundo	Ferrostaal/ SPG	Ausra	Novatec Solar	Solar Euromed	Novatec Solar
Location	Liège, Belgium	PSA, Spain	Liddell, Australia	Calasparra, Spain	Themis platform, France	Calasparra, Spain
Total area	2‘400 m²	1432 m²	18’490 m²	21’571 m²		302’000 m²
Parameters		100m, up to 450°C	Preheating	Sat. steam 50 bars, 1.4 MWe		Sat. steam 55 bars, 30 MWe

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
- …

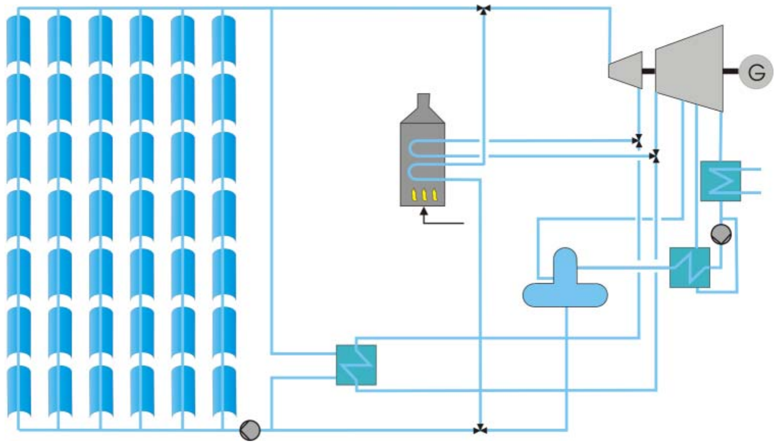
Source: Industrial Solar

LFC Developments > Overview

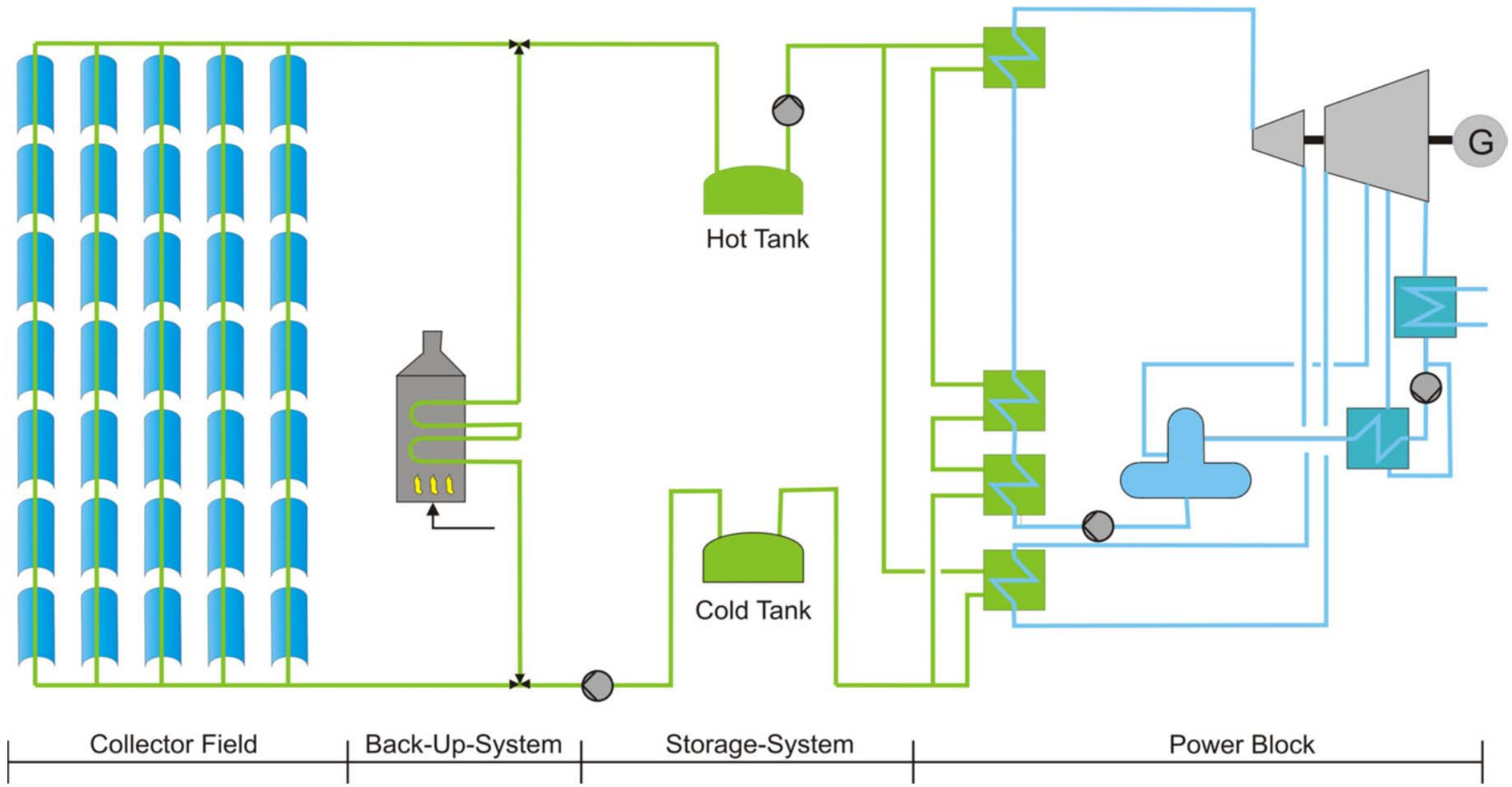
- Use economies of scale
  - Increase degree of automation in production, construction and maintenance
  - Optimize collector design
- Develop receivers for high temperatures
  - Vacuum tube with secondary
  - High temperature coating to become stable at air
  - Secondary reflector to remain stable at 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)

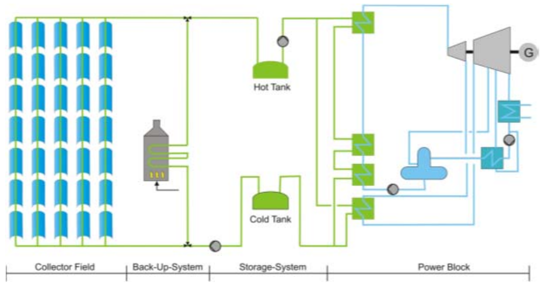


LFC Developments > Plants with Molten Salt

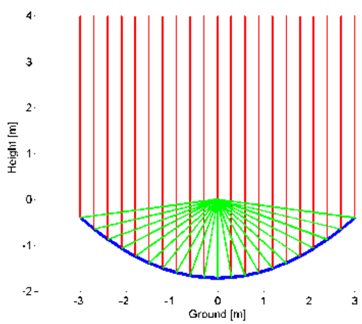


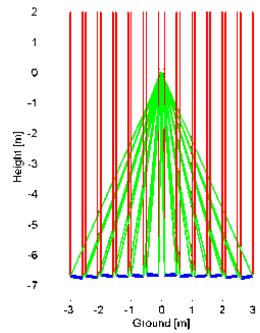
LFC Developments > Plants with Molten Salt

- 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

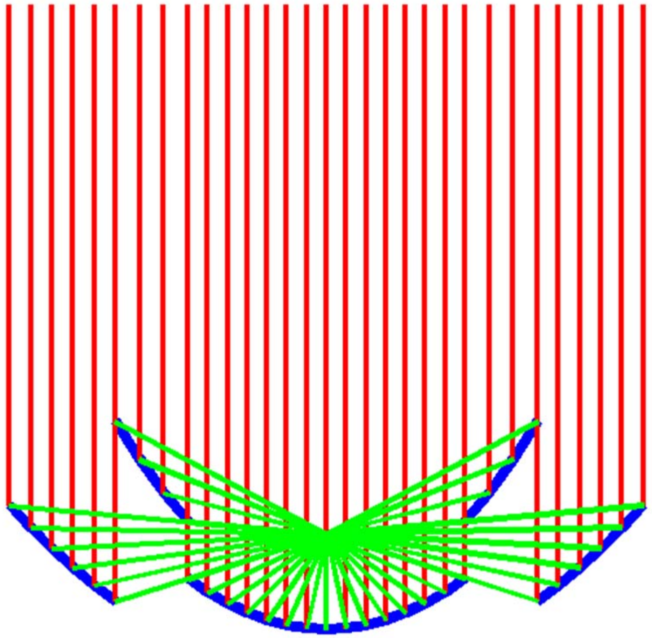




+	-	+	-
High optical efficiency	Flexible tube connections required	Low cost parts and mirrors	Low optical efficiency
Constant output	Wind loads/torque transfer	Low wind loads	Secondary reflector required (usually)
	Few possibilities for cost-reduction		Less operation hours

LFC Developments > Fix Focus Trough

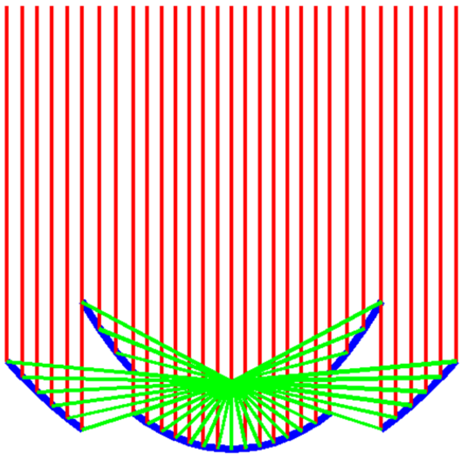
- Combine the best from both worlds:
  - Fix Focus
  - Constant effective aperture intraday
  - Focal line is center of mass
  - No secondary reflector

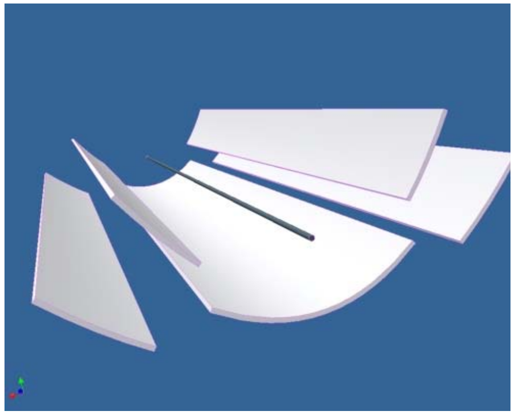


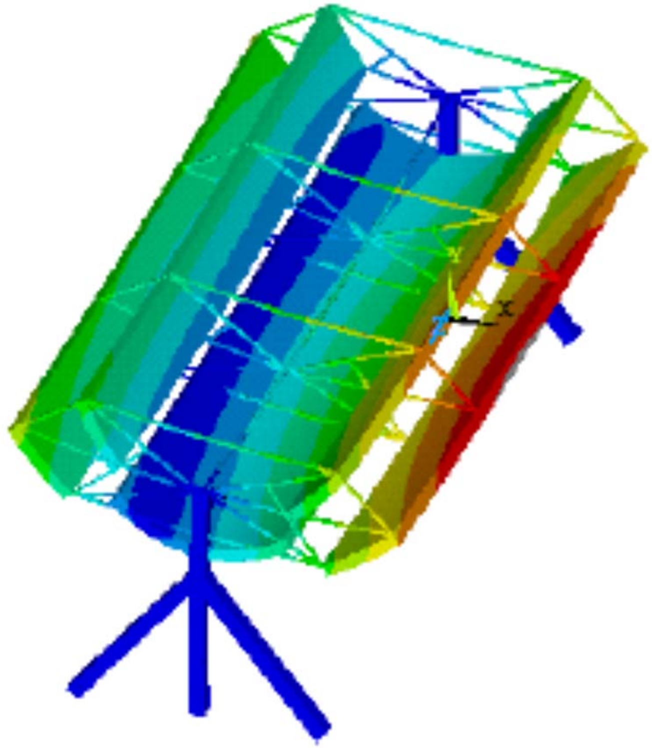
Source: DLR; Prahl, C., Schapitz, T., Uhlig, R.: SolarPACES 2011

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…

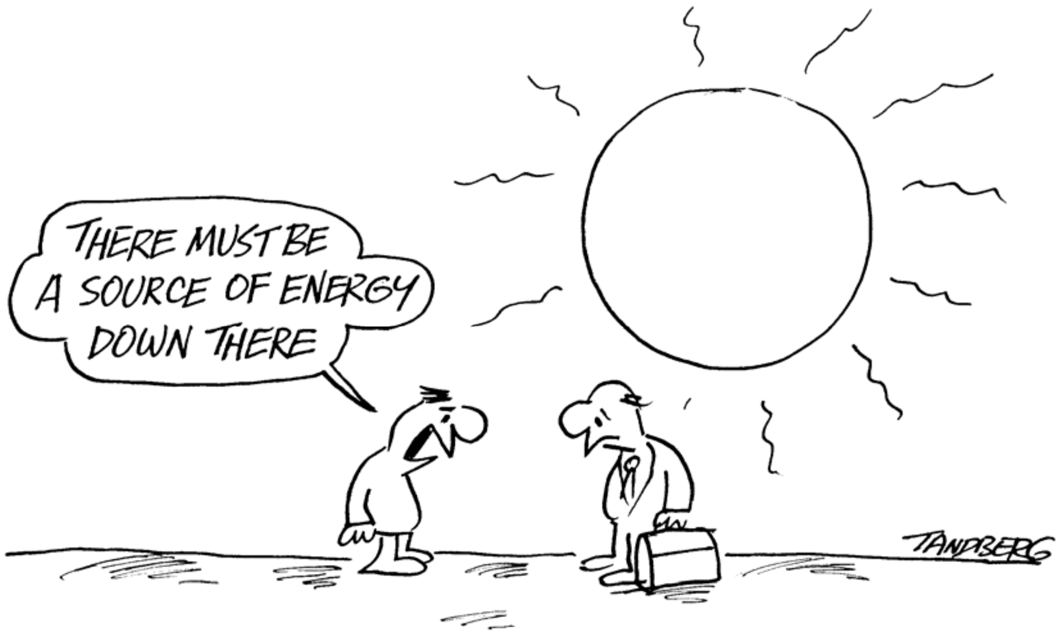
- …fixed receiver pipe → no ball joints
- …trough shape "split" into multiple small mirror facets
- …lower optical performance
- …lower construction cost due to rapid assembly
- …lower susceptibility to wind damage
- …more efficient land use
- …light construction allowing small motors

Future success depending on costs and application…

Source: Novatec Solar

Questions and Discussion…

- Contact: jan.feldhoff@dlr.de



By Ron Tandberg