European Union's Horizon2020 Research and Innovation programme under grant agreement n°823802

SFERA-III 2nd Summer School
October, 5th- 6th, 2021
Almería (Spain)

Lecture:
Innovative design of a linear Fresnel concentrator for Process Heat Applications

Prepared by: Loreto Valenzuela
CIEMAT, Plataforma Solar de Almería
loreto.valenzuela@psa.es

Contents

- Overview on LFC technology
- Optical perfomance
- Innovative design of LFC for SHIP

Introduction

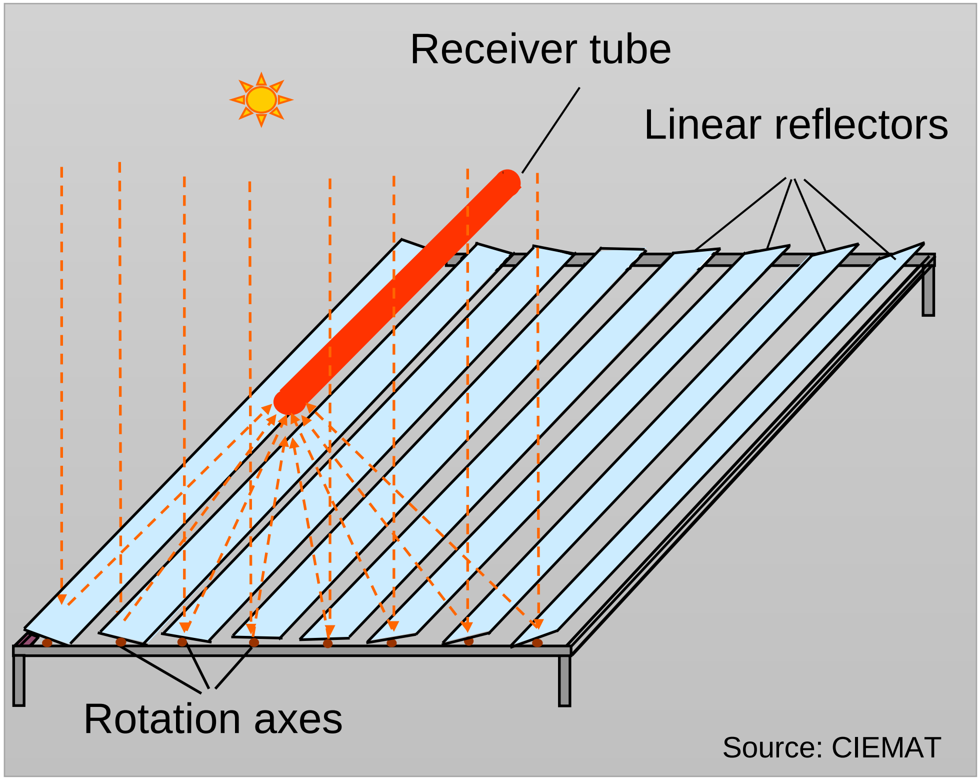
- Linear Fresnel Collector (LFC) is a concentrating solar collector with
  - **fixed** solar **receiver**,
  - **mobile** optical **concentrator**.
- The primary optical concentrator follows a channel shape divided into multiple lineas composed of reflectors.
- Geometric concentration ratio*:

$$C_{geo} = \frac{A_{net}}{A_{rec}}$$

A_{net}: Net reflector area

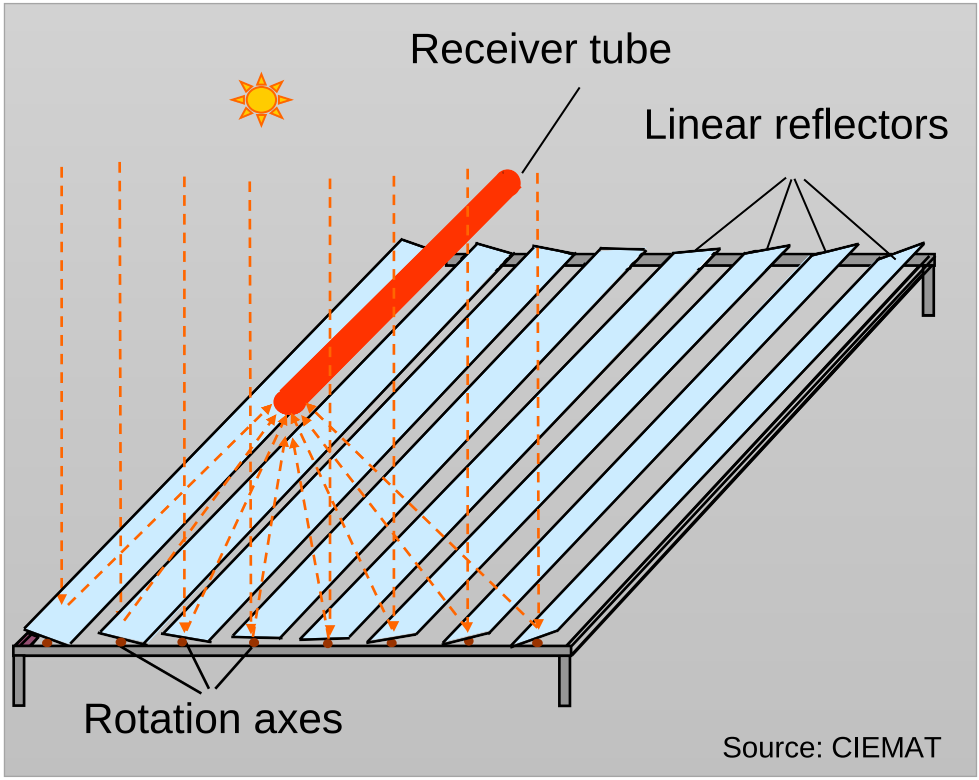
A_{rec}: Receiver area

Values of C_{geo}: ~10 to ~ 100



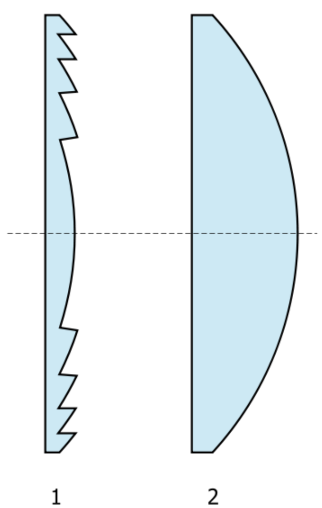
Introduction

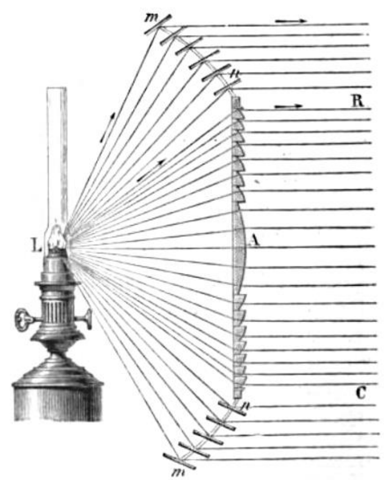
- A **Linear Fresnel Collector (LFC)** can present higher concentration of solar radiation on the receiver surface than a **parabolic trough (PT)**.
- BUT a **LFC** presents lower optical efficiency than a **PTC.**
- LFC technology is cheaper than PTC technology due to the greater simplicity of some components.
- **CHALLENGE for LFC technology:** to compensate for lower efficiency with reduced cost in order to be more competitive.

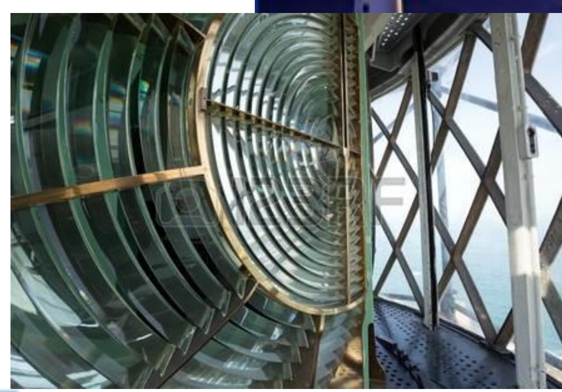


Woring principle of LFC

- Augustin Jean Fresnel (1788-1828), French physicist
- Thin lens (small weight and volume) for short focal lengths
- First application in lighthouses (1823): to focus light horizontally and make it visible over long distances

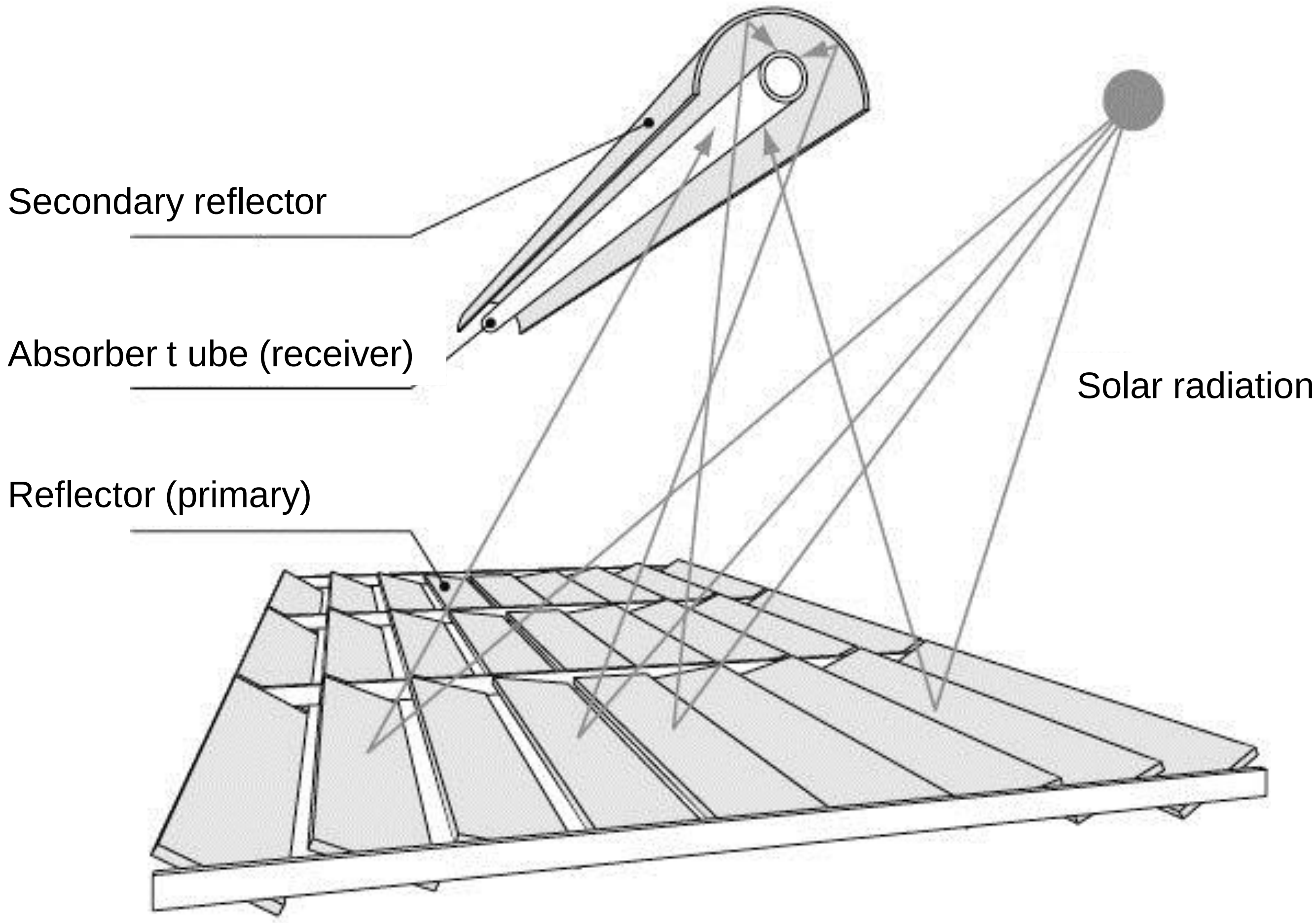






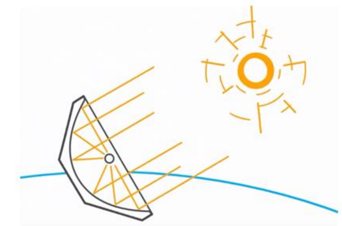
Imágenes: Wikipedia

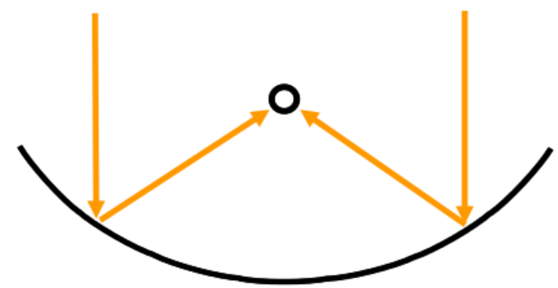
Working principle of LFC

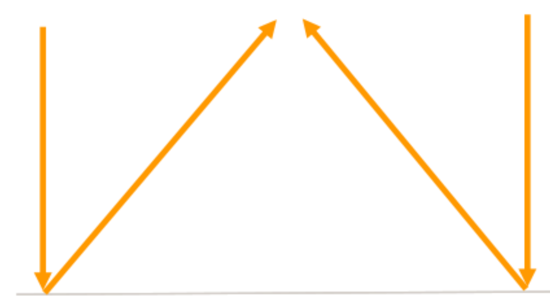


Working principle of LFC

- Compared to a parabolic trough collector, in a LFC the reflectors (mirrors) are all located in the same plane in the standard designs.







Working principle of LFC

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- The optical concentrator of LFC reproduces parabolas with different focal lengths.

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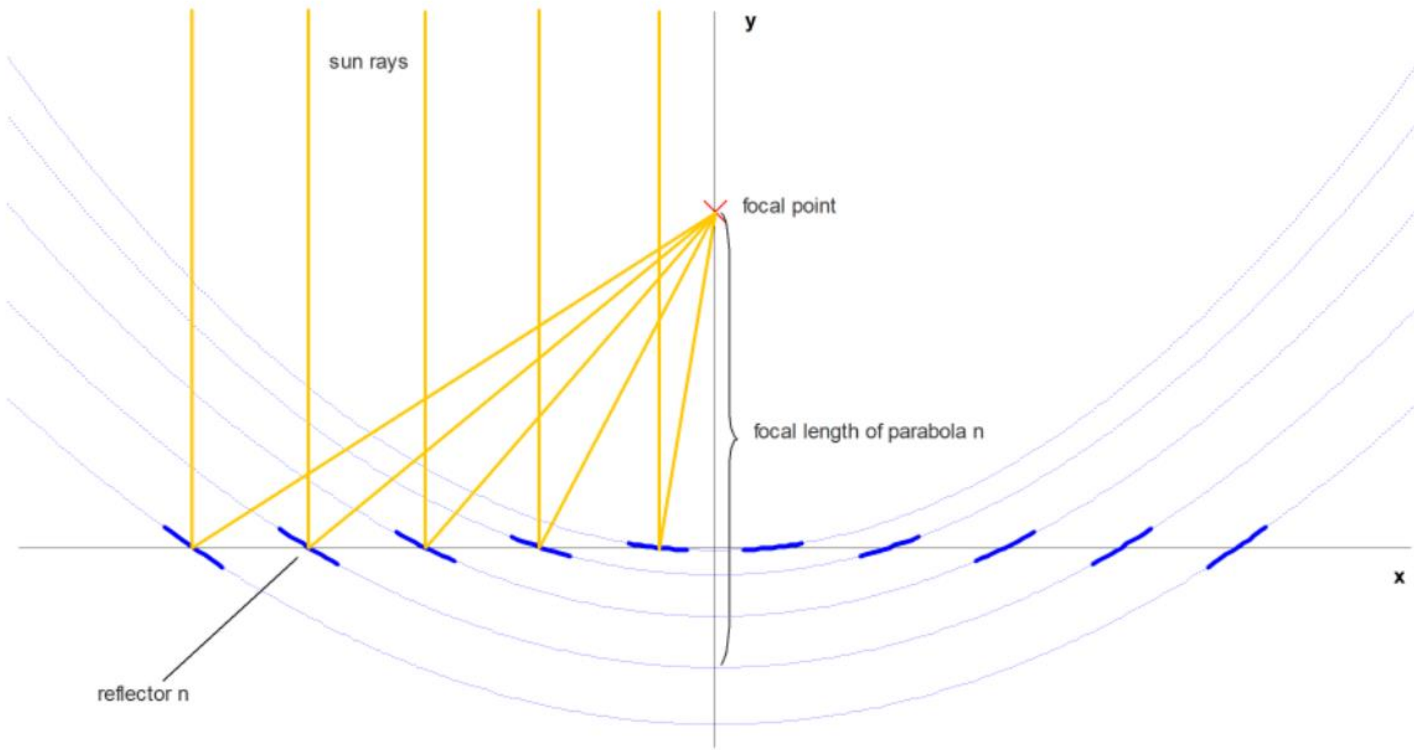
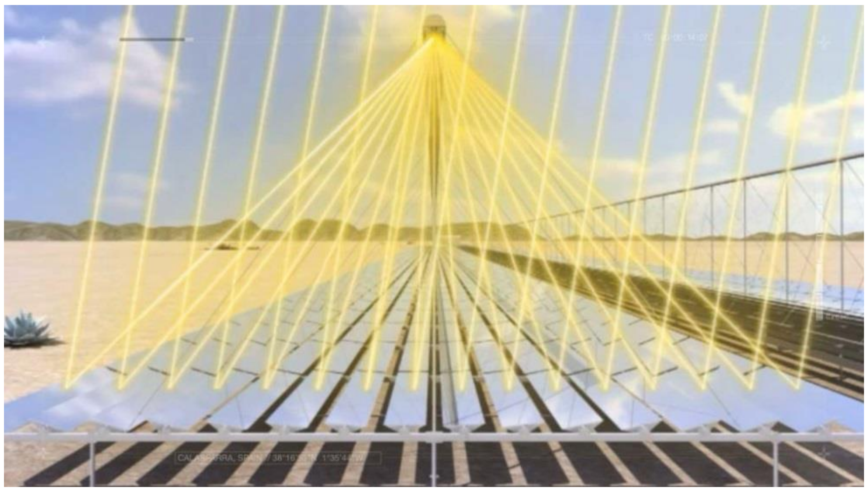
- The optica reproduce different fc



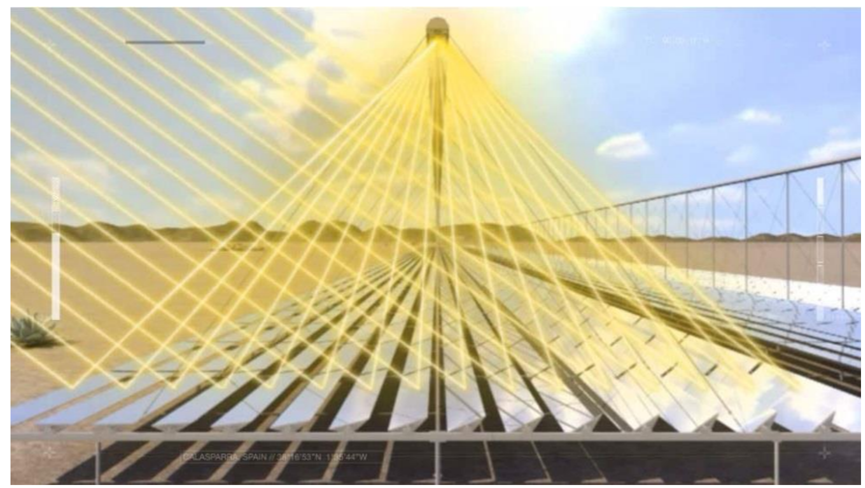
Working principle of LFC

- Compared to a parabolic trough collector, in a LFC the reflectors (mirrors) are all located in the same plane in the standard designs.
- The optical concentrator of LFC reproduces parabolas with different focal lengths.
- It works with incidence of direct solar radiation normal (perpendicular) or not to the plane of aperture.

Working principle of LFC



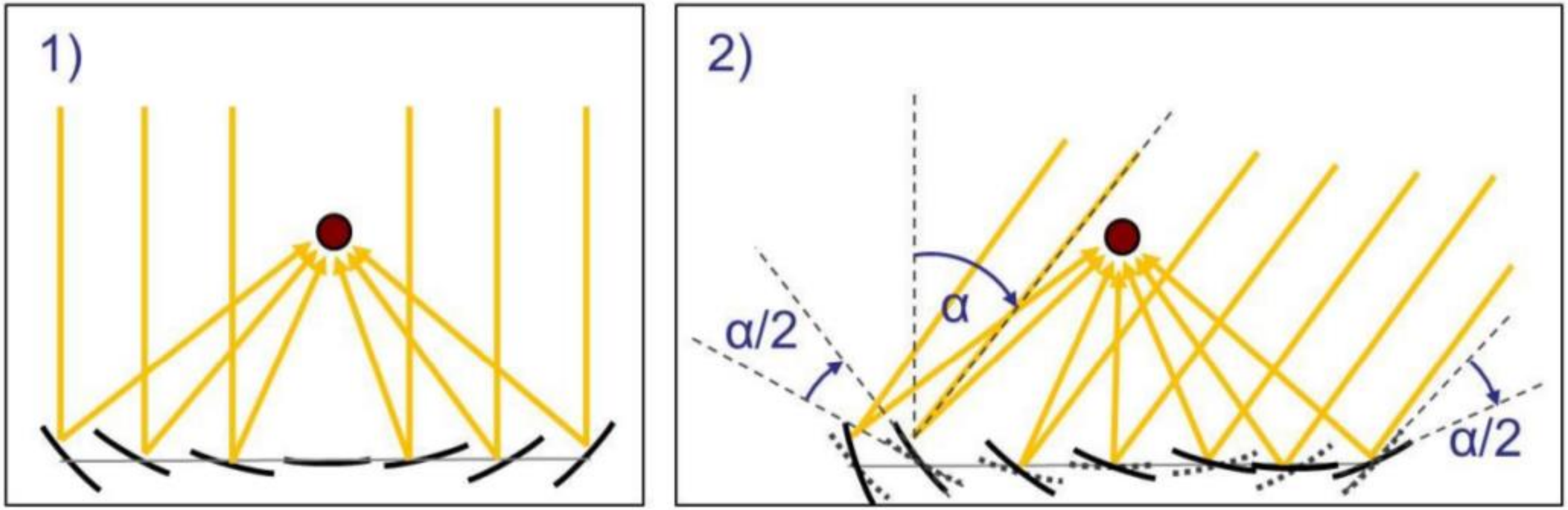
Fuente: NOVATEC Solar (www.novatecsolar.com)



1.4 MWe LFC power plant in Calasparra (Spain) from NOVATEC Solar

Working principle of LFC

- Sun-tracking principle:
  - Each row of reflectors has a different tilt angle.
  - The tilt is directly related to the transversal incidence angle of the solar radiation and reflectors row position.



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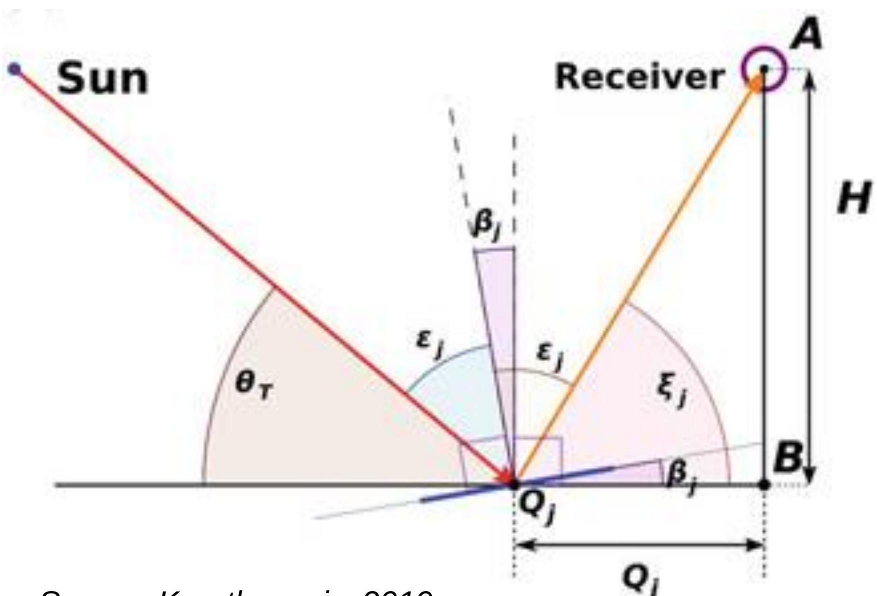
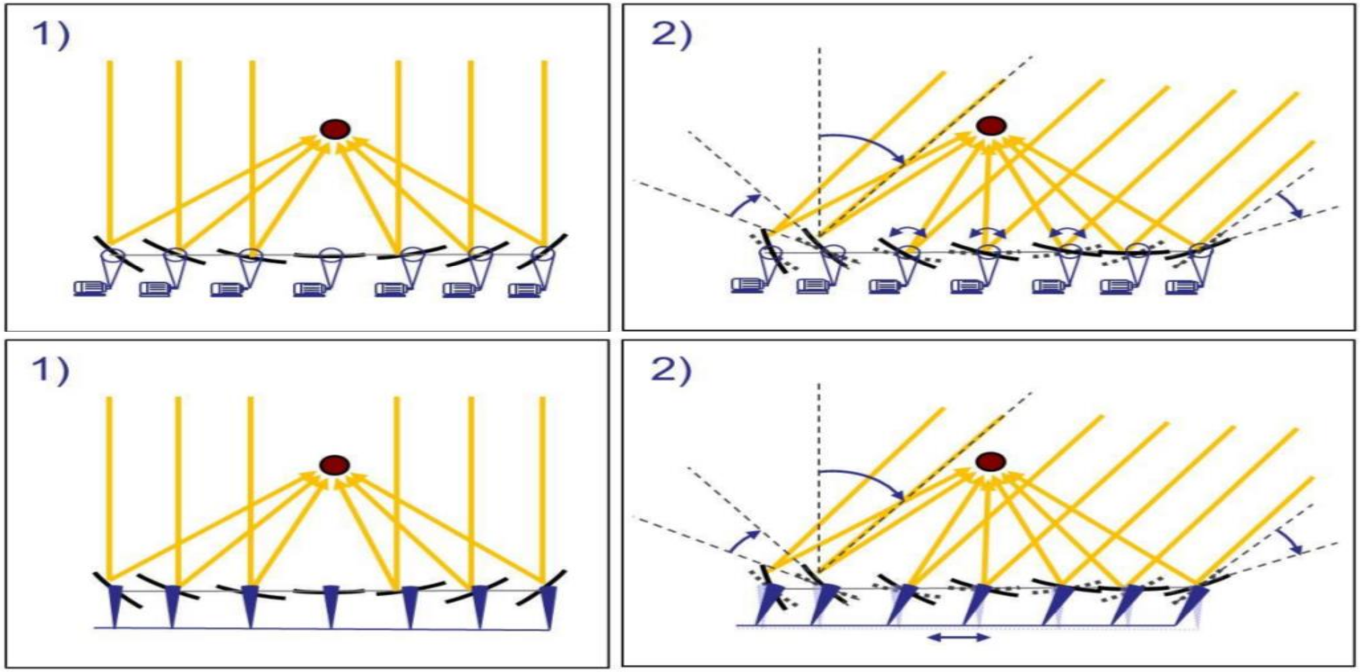


Source: *Karathanasis, 2019*

$$\beta_j = \frac{1}{2}\tan^{-1}\frac{H}{Q_j} - \frac{\theta_T}{2}$$

Working principle of LFC

- Sun-tracking principle:
  - Individual actuators or one-single actuator for the entire set of reflectors making up the primary optical concentrator

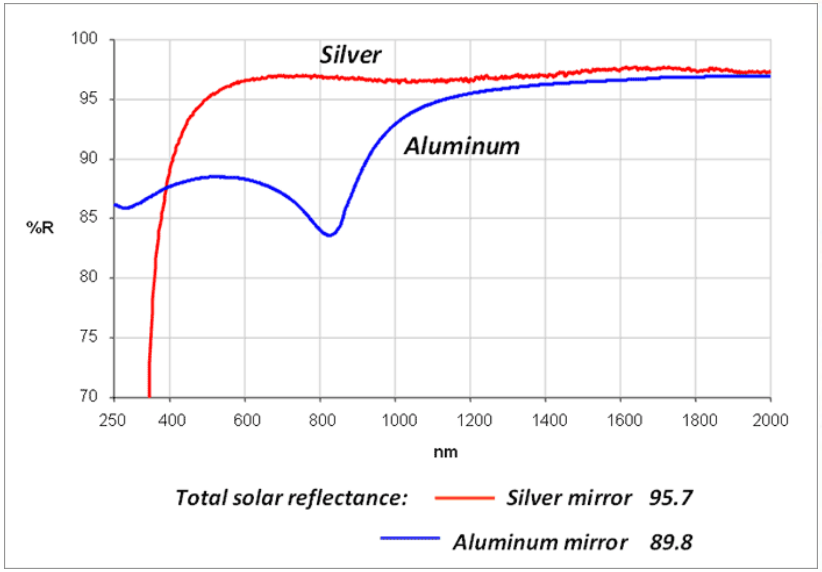


LFC: Components

- Sun-tracking principle:
  - Individual actuators or one-single actuator for the entire set of reflectors making up the primary optical concentrator


LFC: Components

- Reflectors:
  - Flat or slightly curved mirrors (on the supporting structure)
  - Metals used: silver-glass or aluminum mirrors



LFC: Components

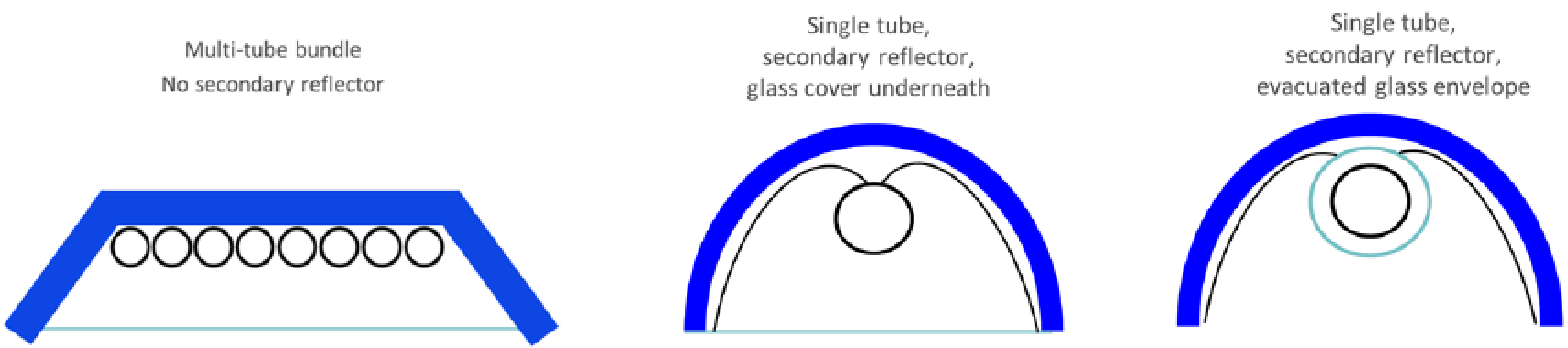
- Reflectors:
  – Flat or slightly curved mirrors (on the supporting structure)

Curvature:
- Cylindrical → preferred
- Parabolic ✘

- Curvature radius of a cylindrical mirror is twice that of a parabolic mirror for the same focal length, which affects the manufacturing process of the mirror support facet.
- Less pronounced cylindrical curvature better supports thin mirrors and reduces the risk of breakage.

LFC: Components

- Receiver:
  - Cavity with parallel tube bundle
  - Non evacuated receiver tube+ secondary reflector
  - Evacuated receiver tube+ secondary reflector



Source: Häberle, 2014

LFC: Components

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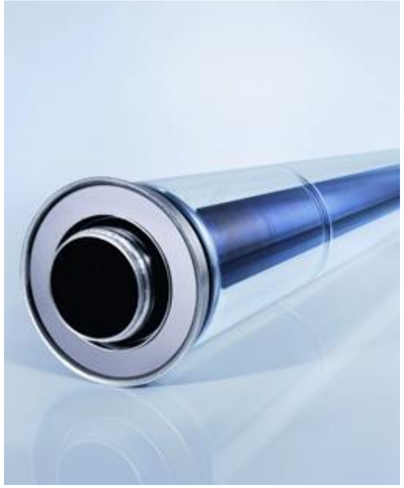

LFC: Components

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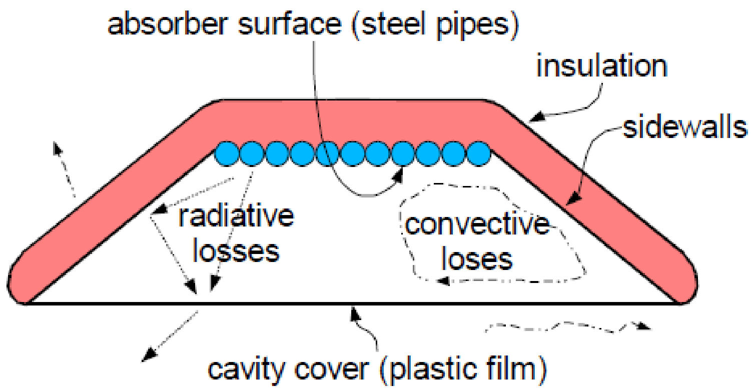
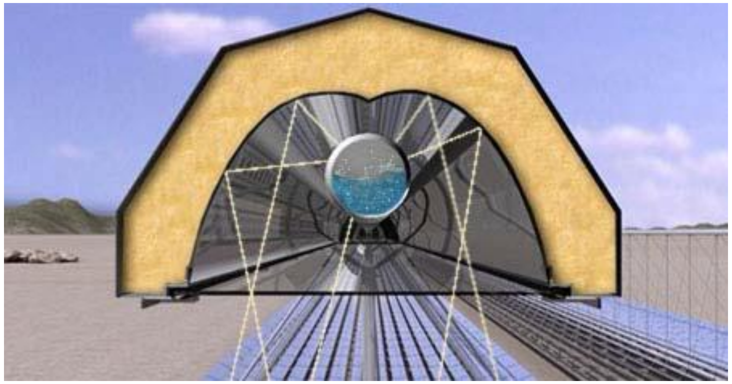


Source: Pye et al. ANZSES, 2003



Source: DLR

LFC: Components

- Reflectors:
  - Flat or slightly curved mirrors (on the supporting structure)
- Receiver:
  - Cavity with parallel tube bundle
  - Non evacuated receiver tube+ secondary reflector
  - Evacuated receiver tube+ secondary reflector
- Heat transfer fluid (HTF):
  - **Water/steam (for power generation and SHIP)**
  - **Thermal oil (for SHIP)**
- HTF temperature @450°C maximum

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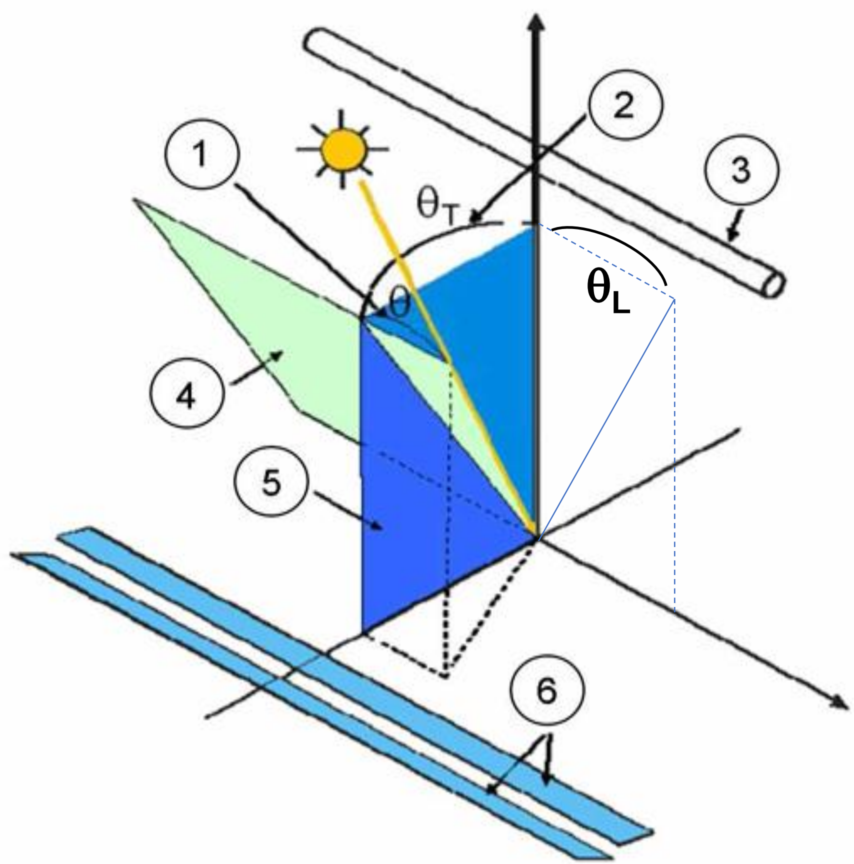
Angle of incidence in a LFC

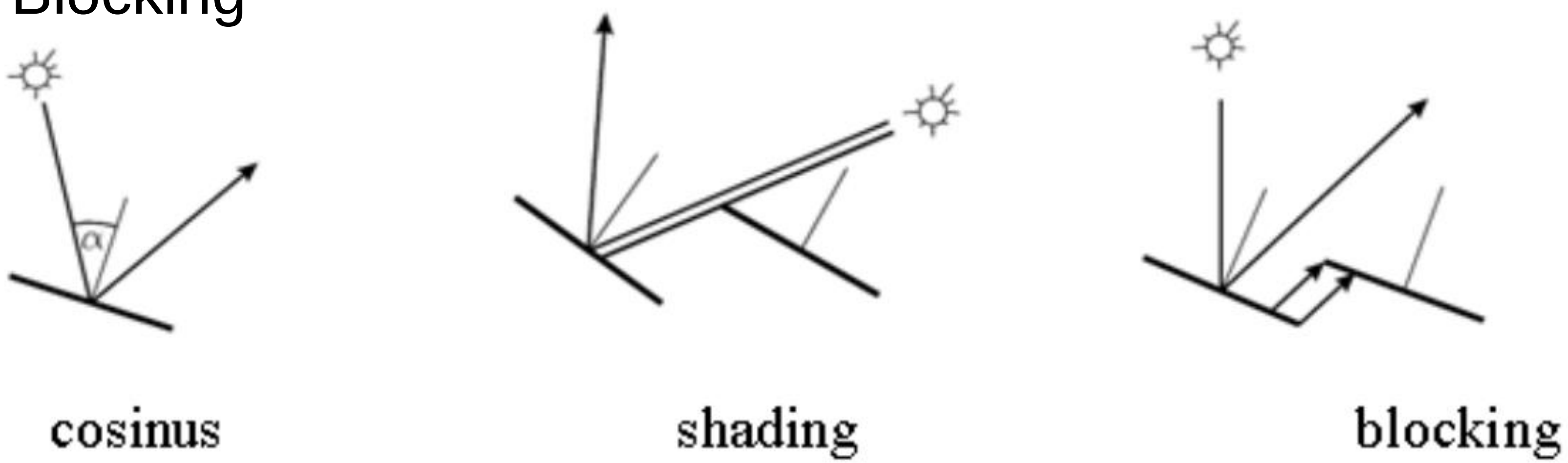
1. **Angle of incidence (θ)**: angle between the straight line to the Sun and the line of intersection between the plane of incidence and the transversal plane.
2. **Transversal angle of incidence (θ_T)**: angle between the line towards the zenith and the projection of the traight line towards the Sun in the transversal plane.

   Longitudinal angle of incidence (θ_L): angle between the zenith and the projection of the straight line towards the Sun in the longitudinal plane.
3. Receiver pipe.
4. Plane of incidence.
5. Transverse plane.
6. Solar reflector rows/lines.



LFC: optical losses

- Cosine factor: effective area of reflection (both in transversal and longitudinal direction)
- End-losses: relevant in the longitudinal direction
- Shading
- Blocking



LFC: optical losses

- The transverse ($\boldsymbol{\theta_T}$) and longitudinal ($\boldsymbol{\theta_L}$) angles of incidence are the main parameters used to characterize the optical performance of a LFC.

- Effective radiation in the receiver:

$$G_b * \cos\theta$$

where G_b is the direct solar radiation

- Optical efficiency of a LFC:

$$\boldsymbol{\eta_{opt} = \eta_{opt,0^\circ} \cdot K(\theta) = \eta_{opt,0^\circ} \cdot K(\theta_L, \theta_T)}$$

where $\eta_{opt,0^\circ}$ is the optical efficiency for θ=0° and $\boldsymbol{K(\theta)}$ corresponds to the **incidence angle modifier** (also found in literature with the acronym IAM).

Factorization method by McIntire (1992): $\boldsymbol{K(\theta_L, \theta_T) = K(\theta_L, 0) \cdot K(0, \theta_T)}$

LFC – optical losses

- Optical efficiency of a CLF:

$$\eta_{opt} = \eta_{opt,0^\circ} \cdot K(\theta) = \eta_{opt,0^\circ} \cdot K(\theta_L, \theta_T)$$

where $\eta_{opt,0^\circ}$ is the optical efficiency for θ=0° and $K(\theta)$ **is the incidence angle modifier** (also found in literature as $IAM(\theta)$)

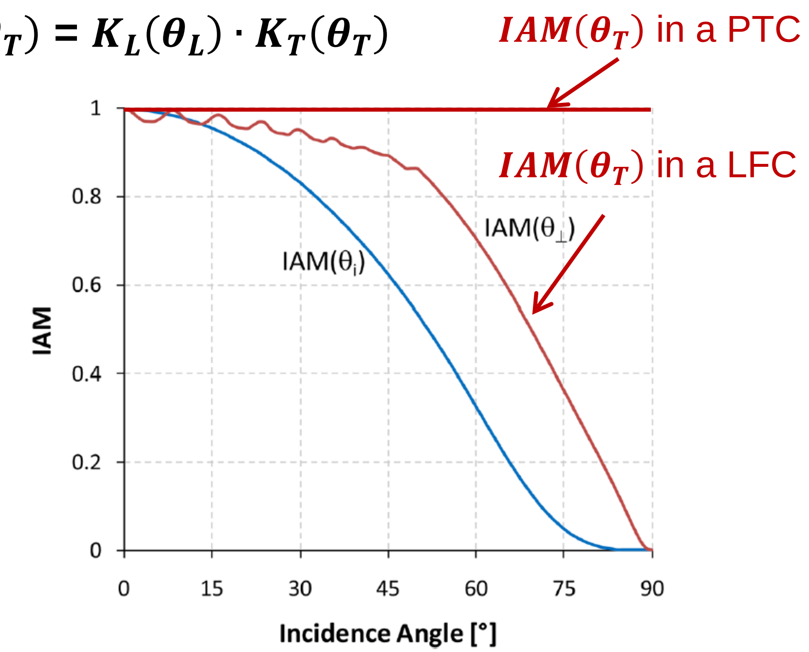
$$K(\theta_L, \theta_T) = K(\theta_L, 0) \cdot K(0, \theta_T) = K_L(\theta_L) \cdot K_T(\theta_T)$$

PTC: $K_T(\theta_T) = 1$

LFC: $K_T(\theta_T) < f(\theta_T) < 1$

LFC & PTC: $K_L(\theta_L)$ are quite similar

L: longitudinal; T: transversal



Source: *Giostri et al, J Solar Energy Eng 135 (2013)*

Contents

- Overview on LFC technology
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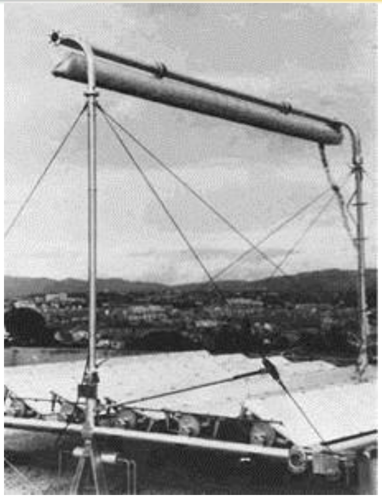
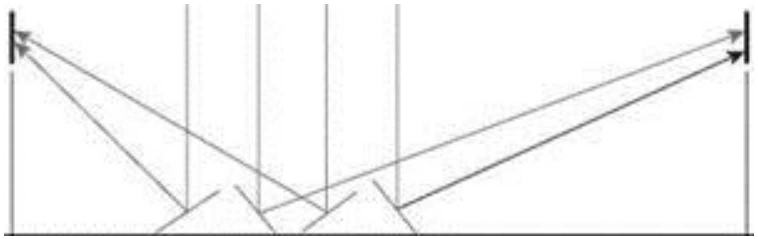
LFC: First designs

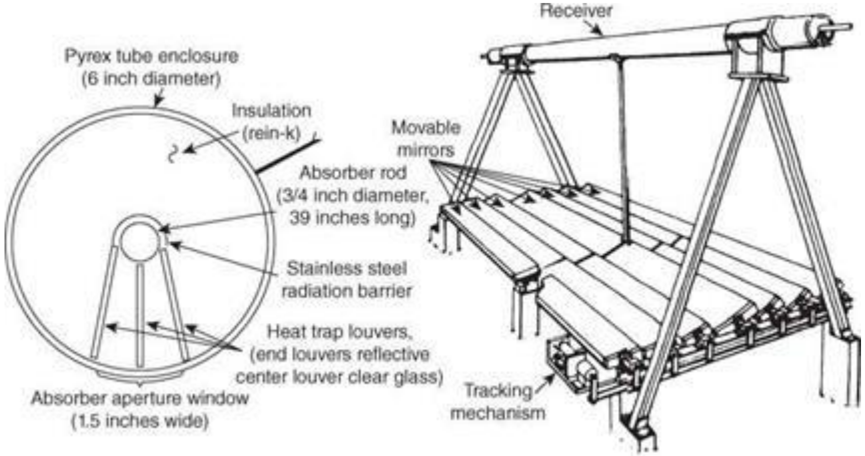
- First prototype in Marsella, France (1961) by Giovanni Francia.
- In the 1970s some companies worked on various design (Suntech, FMC Corporation, etc.).
- In the 1990s Mills developed the CLFR (compact linear Fresnel reflector) concept.



Giovanni Francia, 1961



Primeros esquemas del diseño CLFR (Australia)



6.5 The Itek LFR concept from the 1970s (USOTA, 1978).

LFC: Designs for Solar Power Plants

- Design of the company **AUSRA** (Australia/USA).
- First prototype in 2004, Lidell (Australia)
- 5 MW_e power plant in Bakersfield (California), 2008
- In 2010 the French company AREVA bought AUSRA and its LFC technology.
- Non-evacuated bundle receiver, and secondary reflector in a trapezoidal cavity

Lidell (Australia), Source: John Pye

Bakesrsfield (USA), Source: www.ausra.com

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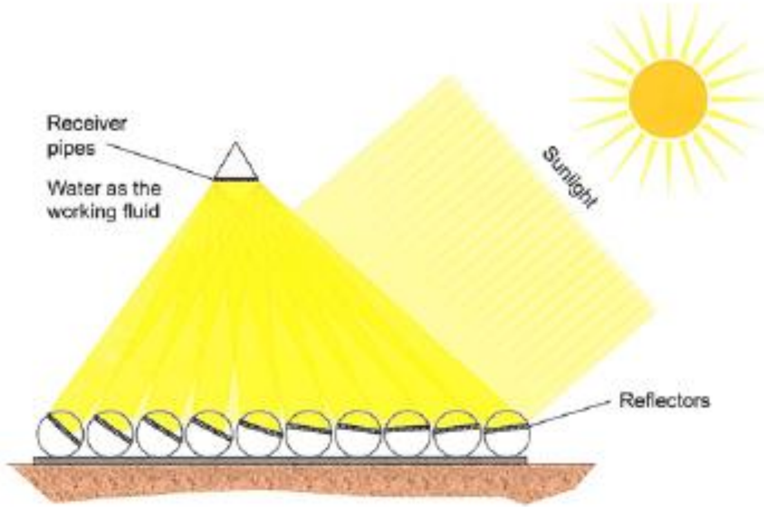
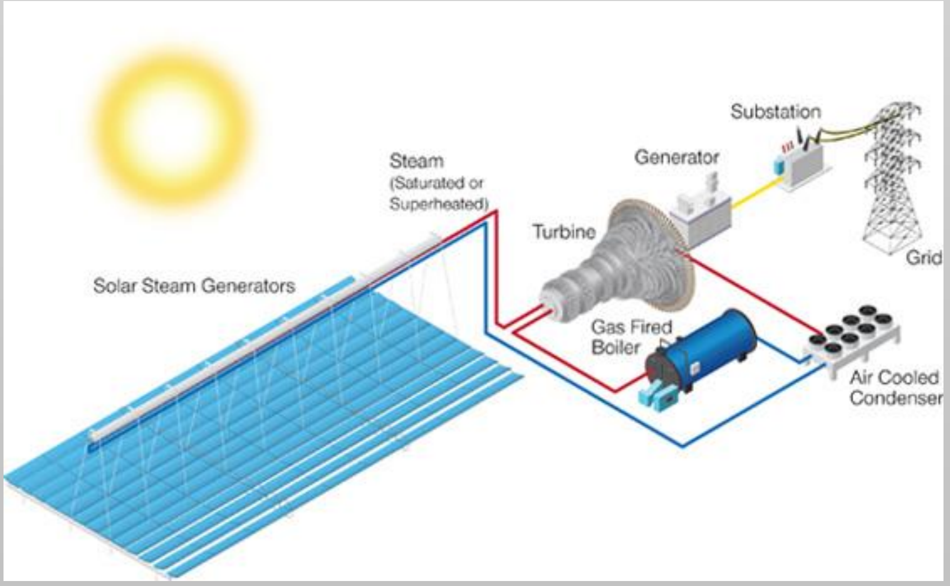


Source: Areva Solar

LFC: Solar Power plant configuration

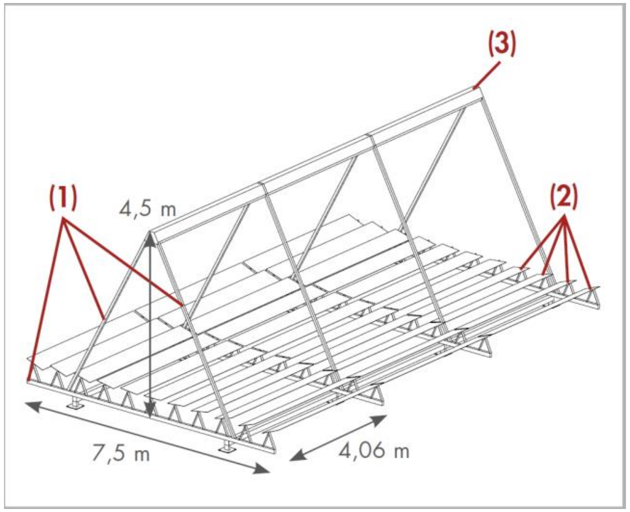
- LFC solar field directly integrated in the power cycle in the power plants in operation (steam cycle).
- Solar field is configurated as:
  - Boiler
  - Boiler + superheater
- Low-medium grid stability (No LDES or auxiliary system used in existing systems)
- LDES for direct steam generation technology is not fully developed. Use of steam accumulators.

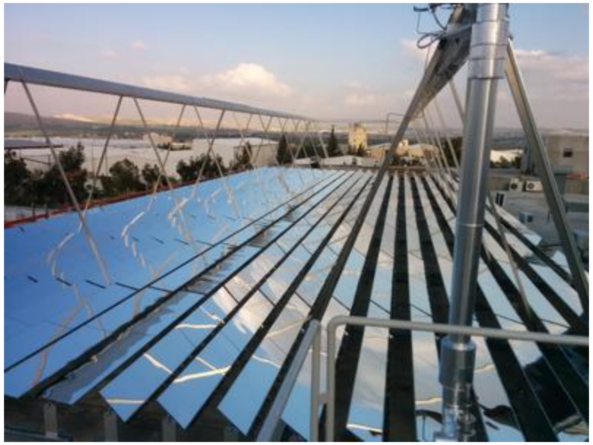


Source: AREVA

LFC: Designs for SHIP

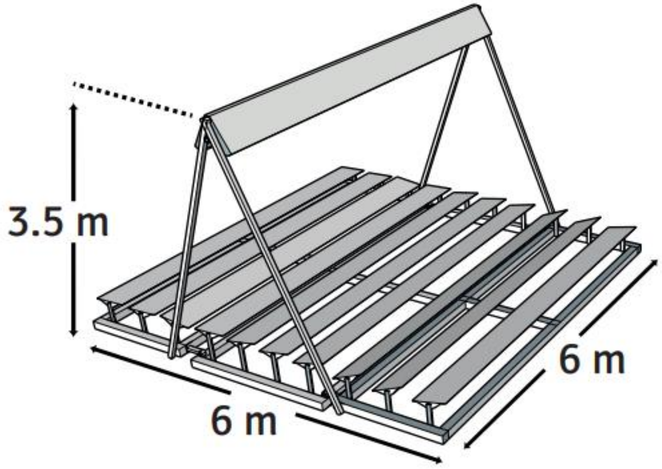
- **Industrial Solar** (**GE**) **LF-11** design (www.industrial-solar.de)
- Collector area: 22 m^2/module
- Triangulr receiver support structure
- Evacuated tube receiver and secondary reflector
- Several commercial projects.
- Solar heat generation
- Design @120bar (standard 40 bar) @400ºC





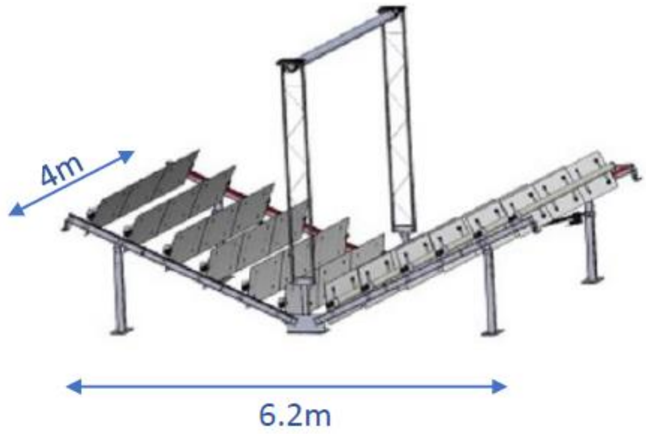
LFC: Designs for SHIP

- **SOLATOM** (**ES**) **FLT-20** design (www.solatom.com)
- Collector area: 26.4 m^2/module
- Triangular receiver support structure
- Transport and assembly for container transport
- Evacuated tube receiver and secondary reflector
- Commercial projects.
- Solar heat generation



LFC: Designs for SHIP

- **Rioglass (ES) Sun2Heat** design (www.rioglass.com)
- Collector area: 25 m^2/module
- Central pylon receiver support structure
- Evacuated pipe receiver without secondary reflector
- Demonstration projects
- Solar heat generation



Módulo unitario: 25m^2 (6,2m ancho x 4m largo)

Innovative LFC for SHIP

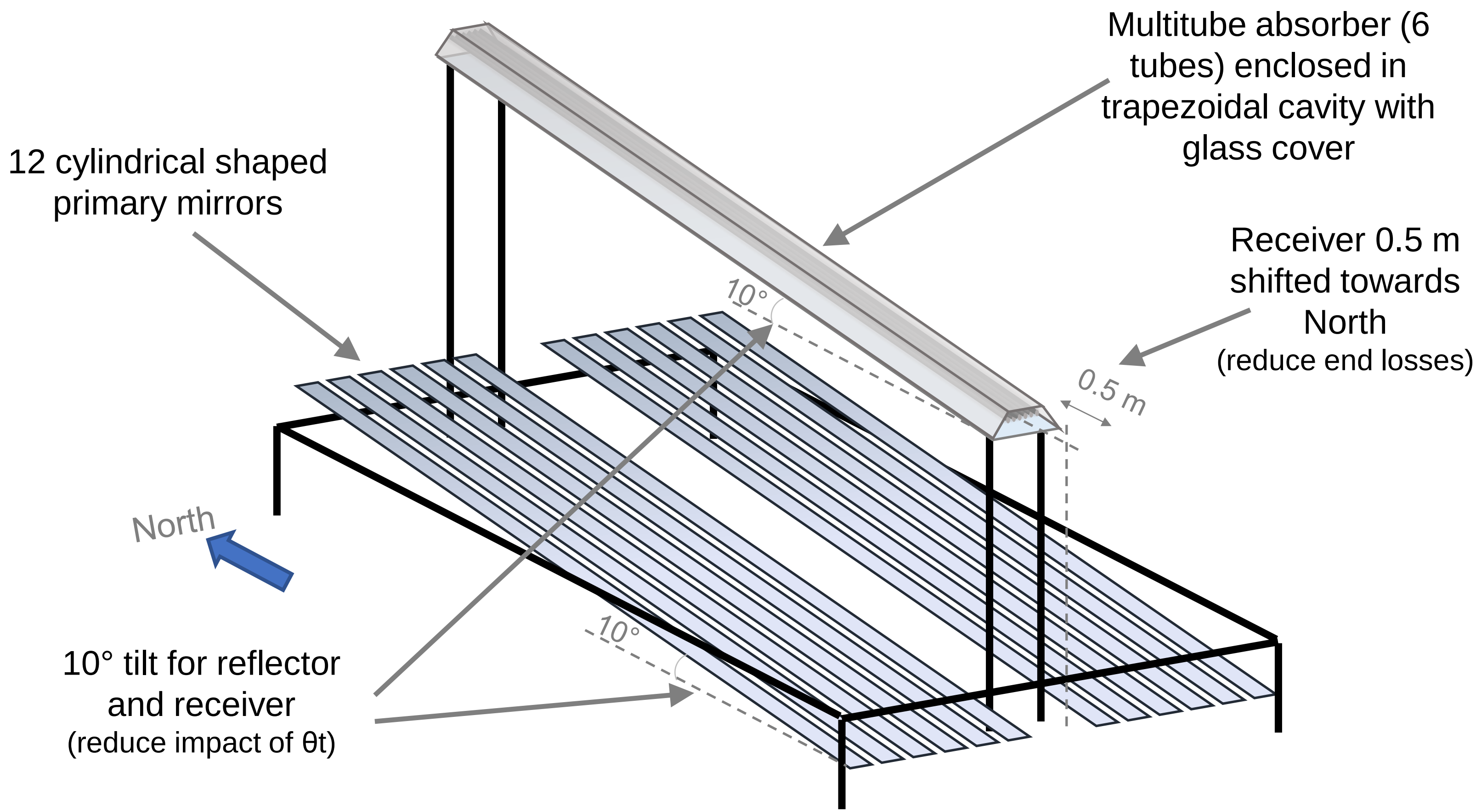
SOLTERMIN

- **PSA design – SOLTERMIN project (2018-2021)**
- Features of the innovative LFC:
  - Development of a prototype of LFC for SHIP applications and integration both on the ground and building roofs.
  - Includes modifications to the standard LFC geometries to increase the optical performance:
    - ➢ Inclination of the primary concentrator to the South
    - ➢ Division of the primary concentrator into two frames that can be also rotated to the East-West up to 30º
    - ➢ Receiver tilt and longitudinal displacement of the receiver to also contribute to optical efficiency increment and reduce end-losses.

Innovative LFC for SHIP

SOLTERMIN

- **PSA design – Main features**



Innovative LFC for SHIP

SOLTERMIN

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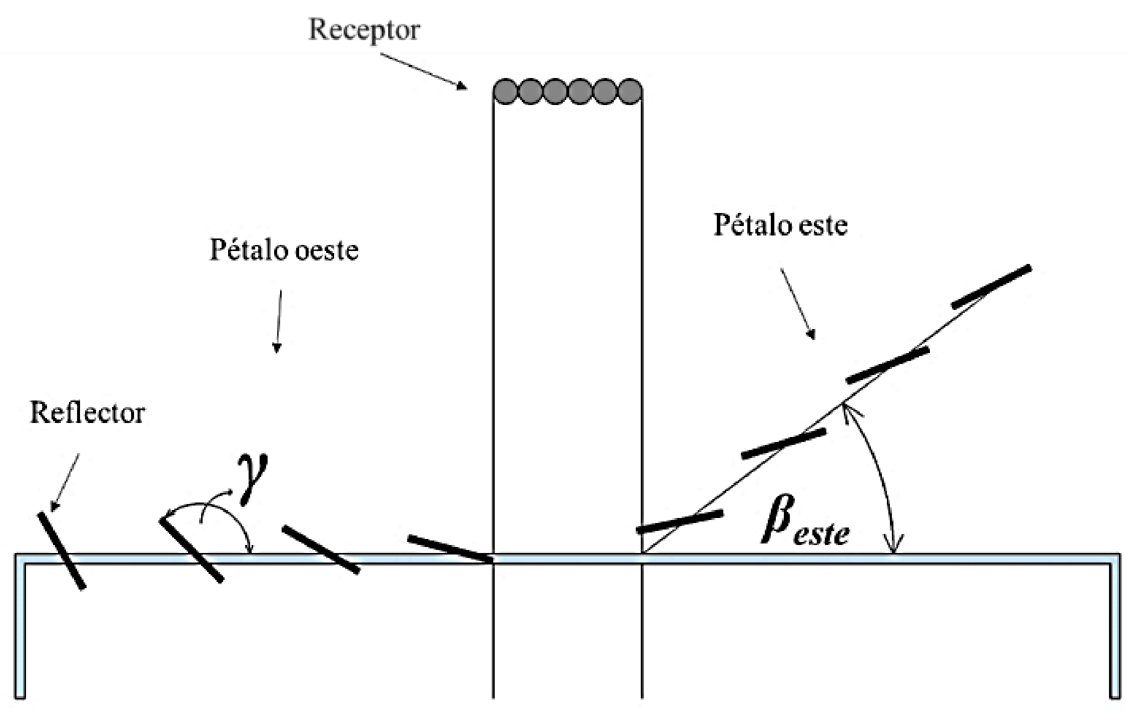
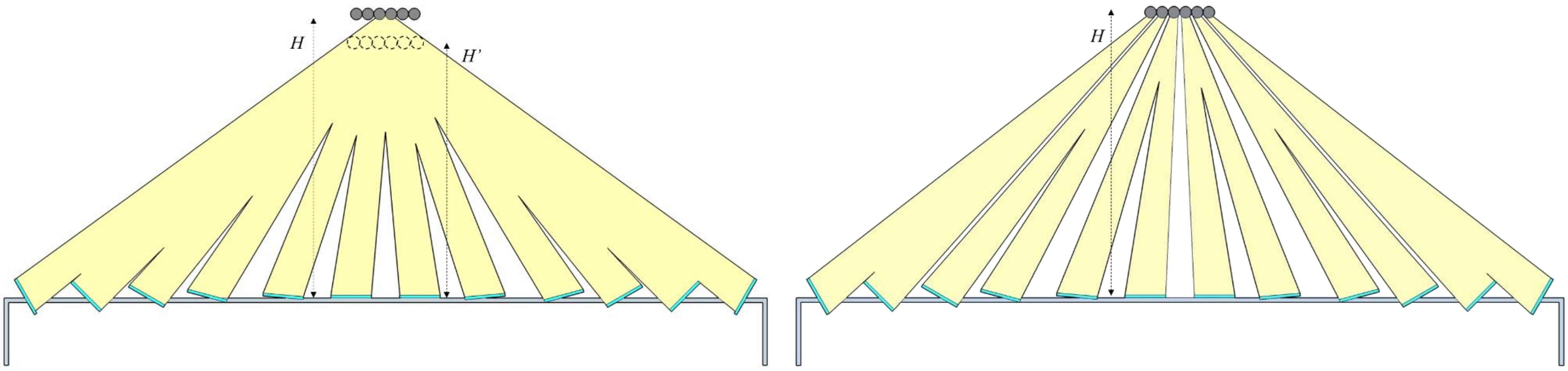


Innovative LFC for SHIP

SOLTERMIN

- **PSA design: Targeting strategy at the receiver**



Innovative LFC for SHIP

SOLTERMIN

- **PSA design: Contributions of** the different **features to** the **optical performance increase →** IAM ↑

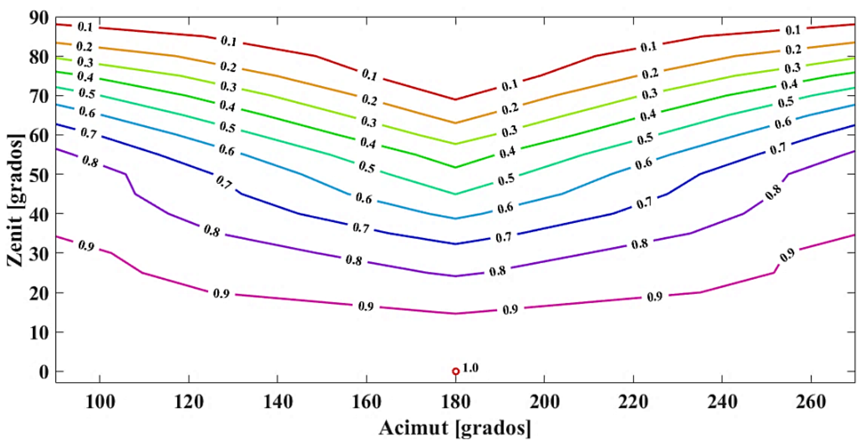


Figura 3.12 IAM del captador sin modificaciones (λ_0, dz_0 y β_0).

IAM of the LFC **without** the modifications

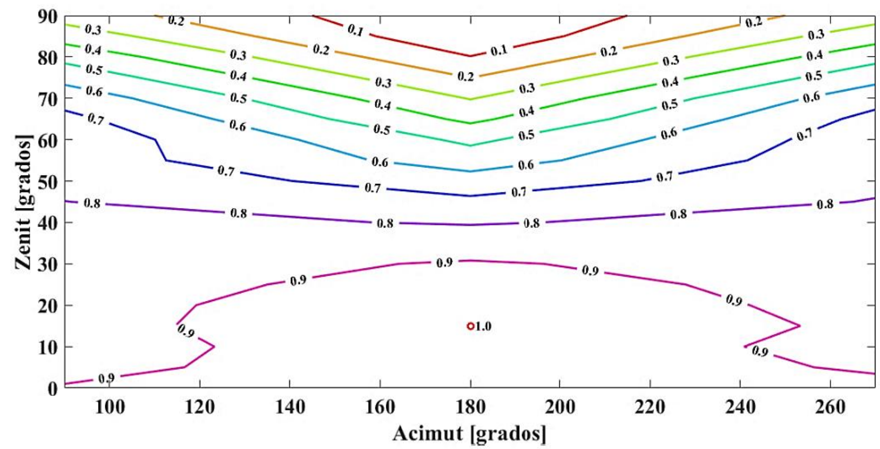


Figura 3.13 IAM del captador con modificaciones (λ_{set}, dz_{opt} y β_{opt}).

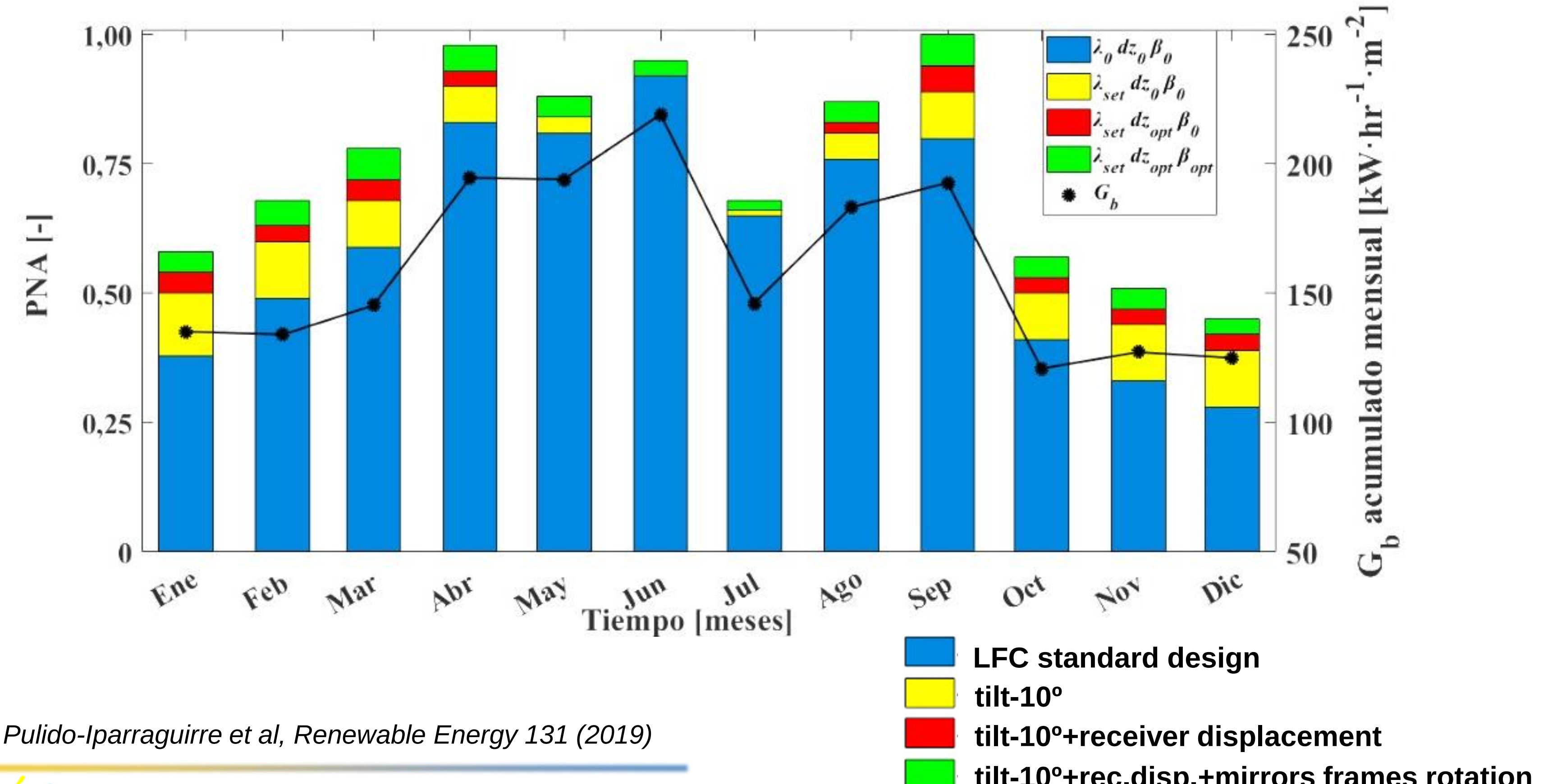
IAM of the LFC **with** the modifications

Source: Pulido-Iparraguirre et al, PhD Thesis (2020)

Innovative LFC for SHIP

SOLTERMIN

- **PSA design: Contributions of** the different **features to** the **optical performance increase**



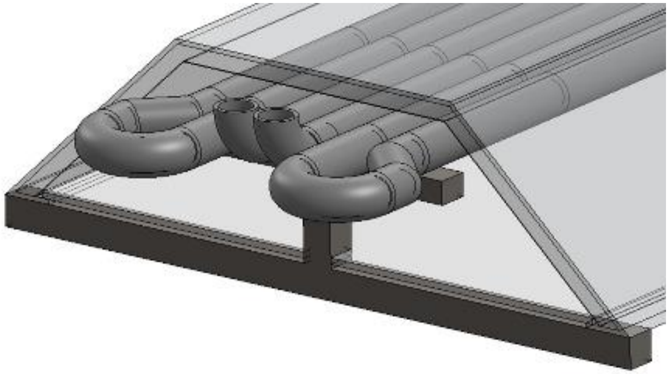
Source: Pulido-Iparraguirre et al, Renewable Energy 131 (2019)

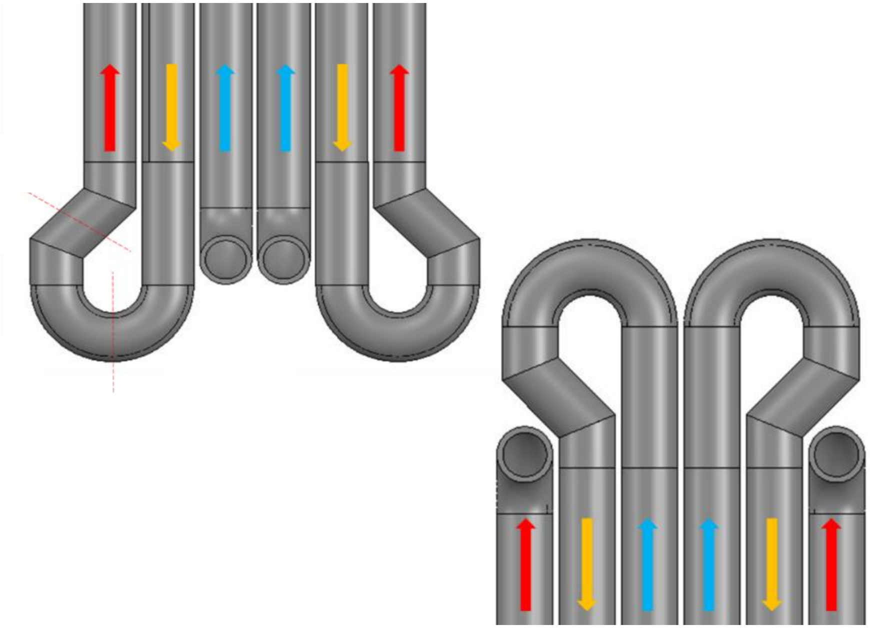
Innovative LFC for SHIP

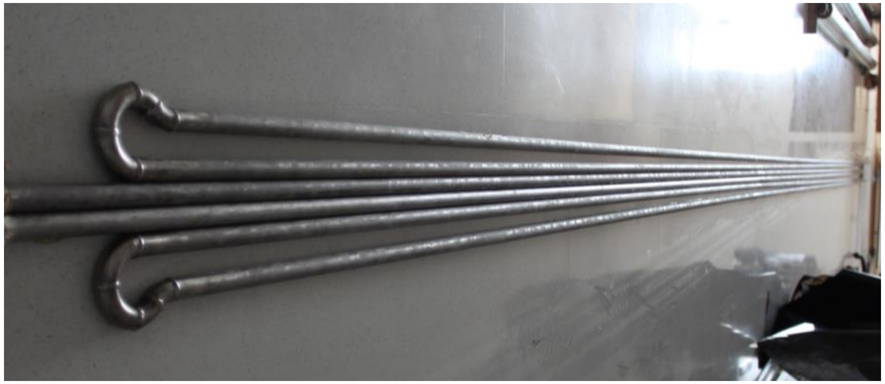
SOLTERMIN

- **PSA design: Other features**

Receiver bundle of ½" stainless steel pipes placed inside a trapezoidal cavity with aluminum reflectors in the inner walls



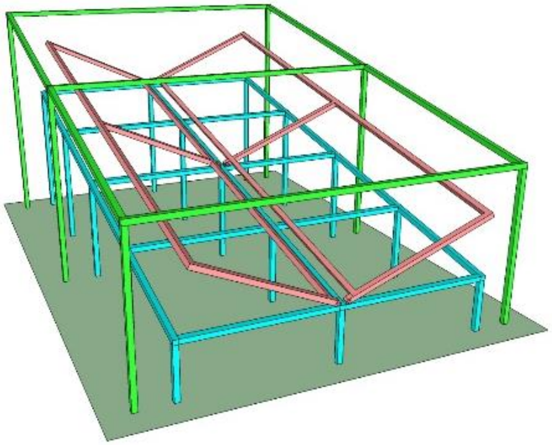




Innovative LFC for SHIP

SOLTERMIN

- **PSA design: Prototype construction**




Innovative LFC for SHIP

SOLTERMIN

• PSA design: Sun-tracking system

- 12 incremental magnetic encoders, resolution 8000 pulses per turn
- 12 units of 24 Vdc gear motors with 2 speeds, one for the fast approach (9 rpm) and another slower for smooth approach and set position during tracking tasks.
- 3 local control units assisted by real-time clock with astronomical algorithm. Each local controller manages 4 reflector lines. MODBUS RTU protocol communications with the main control unit.

Source: García et al, SolarPACES 2021

Innovative LFC for SHIP

SOLTERMIN

- **PSA design: Facets manufactured on-site**
  - 1-mm silvered-glass mirrors from AGC
  - Glued to pre-curved (cylindrical shape) metallic sheet (radius ~ 6.7 m)
  - Durability tests at PSA demonstrated long-term performance
  - Details on the manufacturing process:
    - Pulido-Iparraguirre, D., Valenzuela, L., Fernández-Reche, J., Galindo, J., & Rodríguez, J. (2019). Energies, 12(14), 2795. https://doi.org/10.3390/en12142795

Innovative LFC for SHIP

SOLTERMIN

- **PSA design – Summary of characteristics**

Parameter	**iLFC**
Mirrors width, (m)	0.28
Number of rows (-)	12
Collector Length (m)	10
Gross Collector Area (m^2)	53.2
Net Collector Area (m^2)	33.6
Land Occupation Factor	1.5
Mirror solar reflectance (primary mirrors, glass-silvered), (-)	0.953
Receiver Tube Outer Diameter (mm), Schedule 40 INOX	21.34
Number of tubes in parallel (-)	6
Mirror reflectance (secondary mirrors, aluminum), (-)	0.89
Peak Optical Efficiency, $\eta_{opt,0°}$ (%) (estimated)	63.5

Innovative LFC for SHIP

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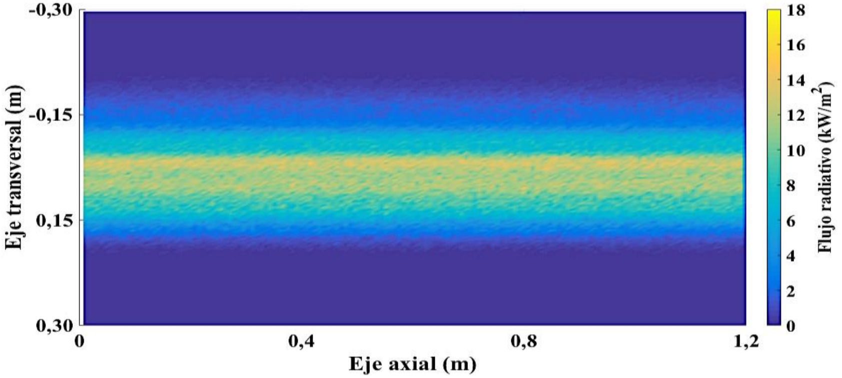
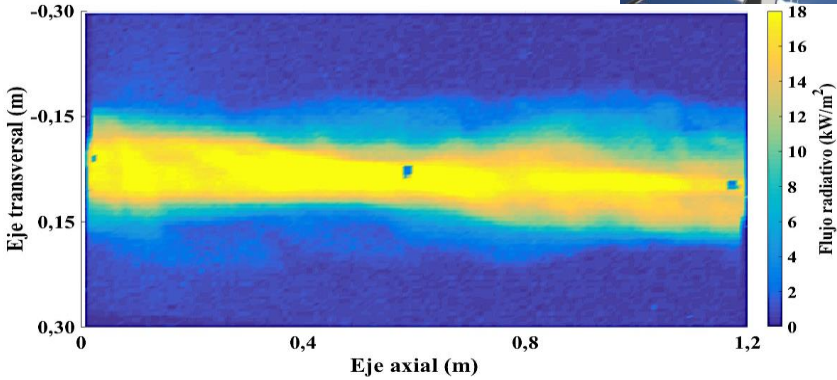
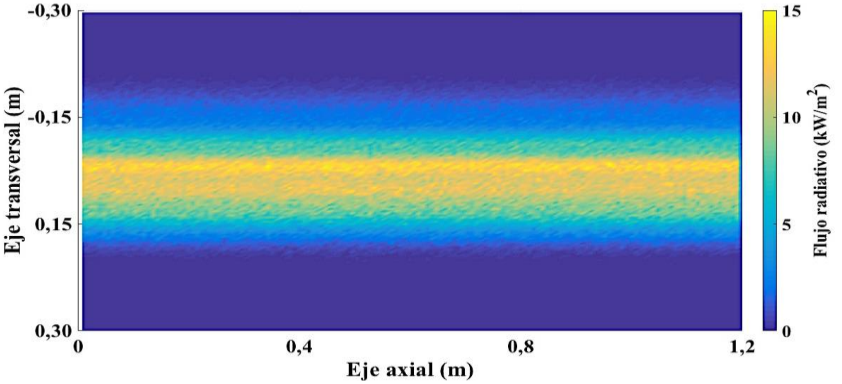
- **PSA design – First flux measurements**

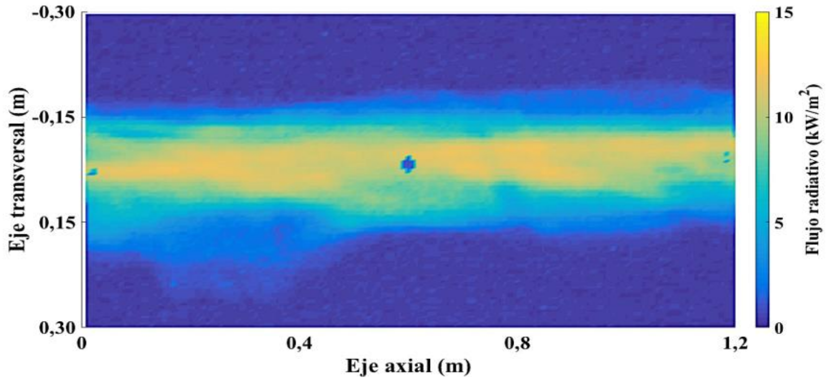
Simulation



Experiments







Source: Pulido-Iparraguirre et al, PhD Thesis (2020)

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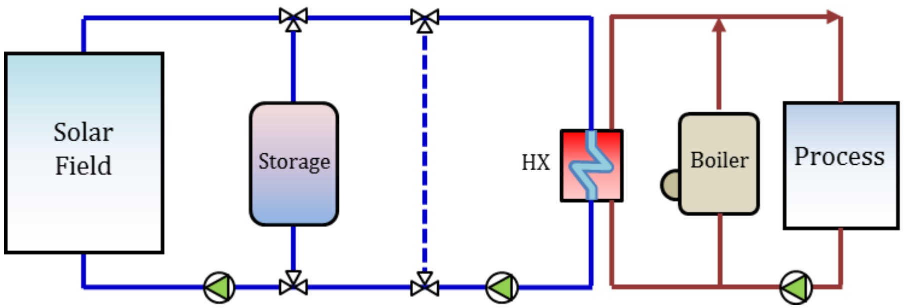
- **PSA design: Techno-economic study**



- Solar field (LFC, PTC or FPC) arranged in loops of collectors. N-S orientation for LFCs & PTCs; FPCs with inclination equivalent to latitude; **LFC with features described <u>except rotation of the two frames</u>**
- Thermal storage: water tank
- Process (IP1 or IP2) fed with solar and/or boiler
- Location: PSA, Spain (37.1° N; 2.36° W); annual DNI = 2071 kWh/m^2

Industrial Process	Solar Collector	Field Loops	Collectors / Loop	Tank Size (m^3)
Dairy/85ºC (IP1)	LFC	6	4	30
Dairy/85ºC (IP1)	PTC	9	4	30
Dairy/85ºC (IP1)	FPC	27	2	30
Beer/165ºC (IP2)	LFC	58	12	500
Beer/165ºC (IP2)	PTC	74	14	500

Source: Biencinto et al, SolarPACES 2021

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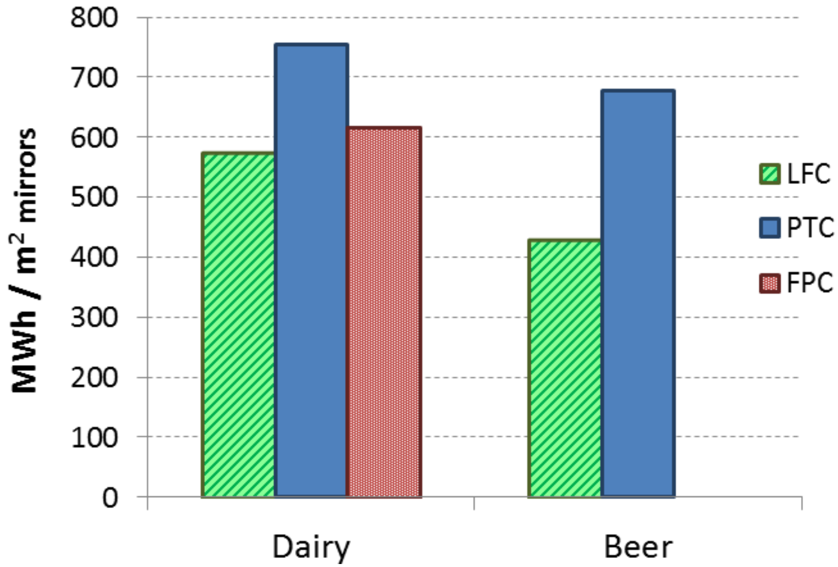
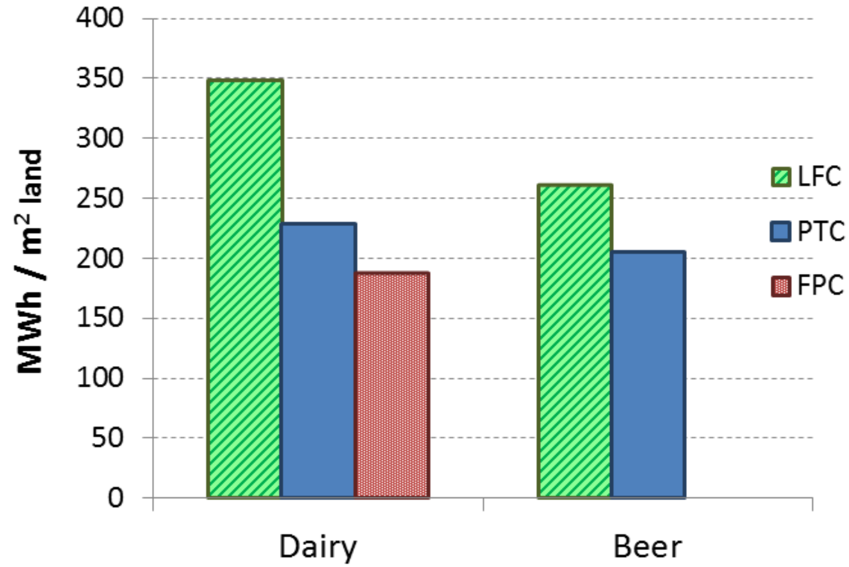
- **PSA design: Techno-economic study**

Annual production per m² of **Mirrors** (collectors) or **Land**:





- **Mirrors**: Higher for PTC and FPC
- **Land**: Higher for innovative LFC (diff. 50-150 MWh/m²), land occupation per m² of collectors ≈ half the value of PTC and FPC

=> Interesting for industrial areas with low space availability

Source: Biencinto et al, SolarPACES 2021

Innovative LFC for SHIP

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- **PSA design: Techno-economic study**

LCoH (*Levelized Cost of Heat*):

$$LCoH = (CRF \cdot K_{invest} + K_{O\&M})/E_{net}$$

- Range for **land costs**: 0…100 €/m² (to reflect variability in industrial areas)
- Two scenarios regarding cost of **solar field** for LFC:
  - Optimistic (**LFC min**): 250 €/m²
  - Pessimistic (**LFC max**): 372 €/m²
- $K_{O\&M}$: 2% of K_{invest} for PTC, 1% for LFC, 0.5% for FPC
- Rest of economic parameters: typical for SHIP

Source: Biencinto et al, SolarPACES 2021

Innovative LFC for SHIP

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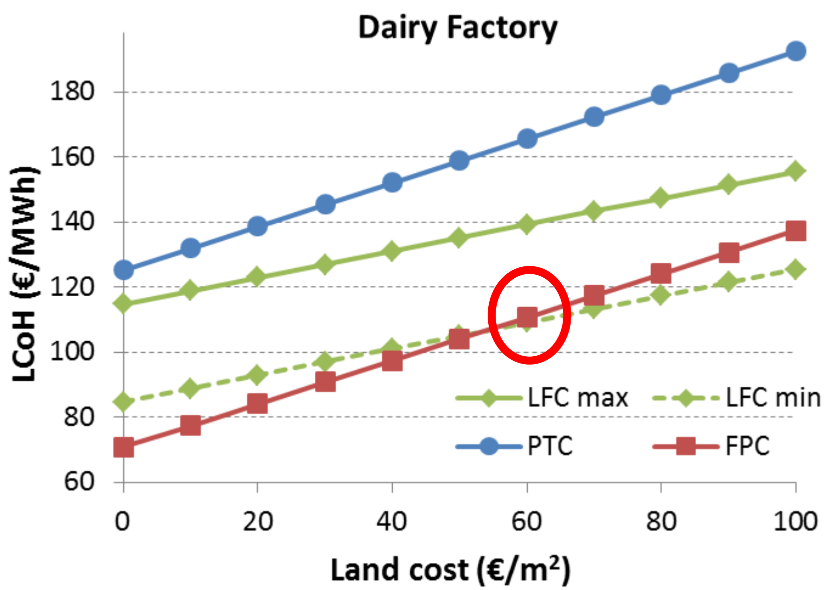
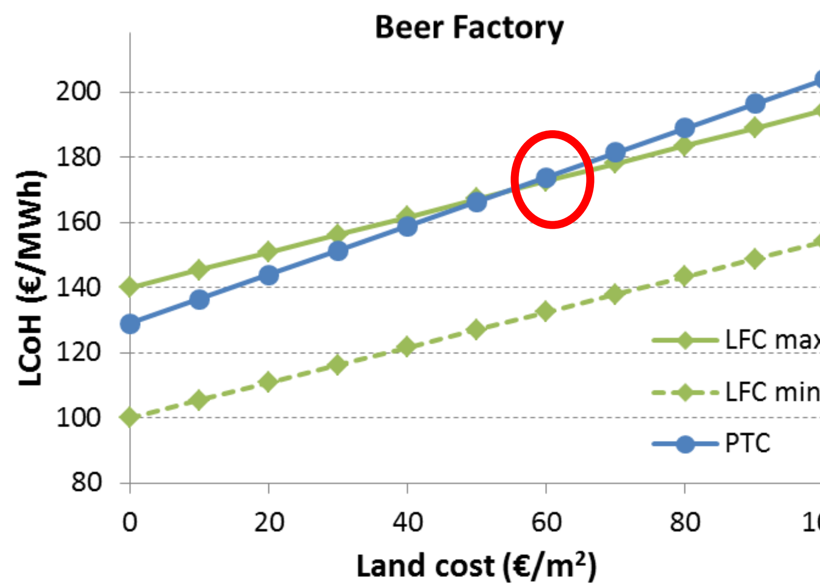
- **PSA design: Techno-economic study**





<u>Innovative LFC</u>:

- Dairy factory: Lower LCoH than FPC for optimistic case and land cost > 60 €/m^2
- Beer factory: Cheaper than PTC in almost all cases (even the pessimistic if land cost > 60 €/m^2)

Source: Biencinto et al, SolarPACES 2021

Innovative LFC for SHIP

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- **Summary**
  - Innovative LFC developed that incorporates features to increase optical performance
  - Innovative LFC suitable for industrial processes with low & medium temperatures for both roof and ground installation
  - Lower production per m^2 of mirrors than similar technologies (PTC, FPC), but higher production per m^2 of land
  - Prototype set-up almost completed at PSA
- **Further steps**
  - Complete the connection of the prototype to one of the hydraulic circuits at PSA to complete its experimental qualification
  - Contact to manufacturing companies to explore industrialization in the construction of the system
  - Promote its penetration in demonstration projects

Innovative LFC

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Patents and publications about the Innovative LFC

1. PCT/ES2018/070059 “Captador Solar Lineal Fresnel Adaptable”, **Int. patent submitted**, January 26, 2018.
2. P202090004 “Captador Solar Lineal Fresnel Adaptable”, **Spanish patent submitted**, February 20, 2020.
3. CVE 1846167, “Captador Solar Lineal Fresnel Adaptable”, **Chilean patent submitted**, November 10, 2020.
4. Pulido-Iparraguirre, D., Valenzuela, L., Serrano-Aguilera, J.J., Fernández-García, A. Optimizing design of a linear Fresnel reflector for process heat supply. Conference Proceedings of **EuroSun 2016**, Palma de Mallorca (Spain), 11-14 October, 2016. https://doi.org/10.18086/eurosun.2016.02.21
5. Pulido-Iparraguirre, D., Valenzuela, L., Serrano-Aguilera, J.-J., & Fernández-García, A. (2019). Optimized design of a linear Fresnel reflector for solar process heat applications. **Renewable Energy**, 131, 1089–1106. https://doi.org/10.1016/j.renene.2018.08.018
6. Pulido-Iparraguirre, D., Valenzuela, L., Fernández-Reche, J., Galindo, J., & Rodríguez, J. (2019). Design, Manufacturing and Characterization of Linear Fresnel Reflector’s Facets. **Energies**, 12(14), 2795. https://doi.org/10.3390/en1214279
7. Pulido-Iparraguirre, D. **PhD Thesis**, University of Almería, 2020.
8. Garcia, G., Egea, A., Valenzuela, L. Pulido-Iparraguirre, D. Advanced sun-tracking control for an Innovative Linear Fresnel Collector. **SolarPACES 2021** Conference, Online Event, September 2021.
9. Alcalde, S., Valenzuela, L., Serrano-Aguilera, J.J. Numerical Investigation of a trapezoidal cavity multi-tube receiver for a Linear Fresnel Collector. **SolarPACES 2021** Conference, Online Event, September 2021.
10. Biencinto, M., González, L., Valenzuela, L. Simulation and Economic Analysis of an Innovative Compact Linear Fresnel Collector coupled to Two Industrial Processes with Low and Medium Temperatures. **SolarPACES 2021** Conference, Online Event, September 2021.

Solar Facilities for the European Research Area

SFERA-III
2nd Summer School
October, 5th- 6th, 2021
Almería (Spain)

End of Presentation

Thank you for your attention

Questions ?

Prepared by: Loreto Valenzuela Gutiérrez
CIEMAT – Plataforma Solar de Almería
loreto.valenzuela@psa.es

This work is also part of the Spanish Project **SOLTERMIN** (Ref. ENE2017-83973-R), supported by the *Programa Estatal de Investigación, Desarrollo e Innovación orientada a los Retos de la Sociedad* (National Program of Research, Development and Innovation oriented to Society's Challenges) of the Spanish Government and co-funded by European Regional Development Fund (ERDF).