STE plants with parabolic trough collectors

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Concentrating Solar Thermal Systems

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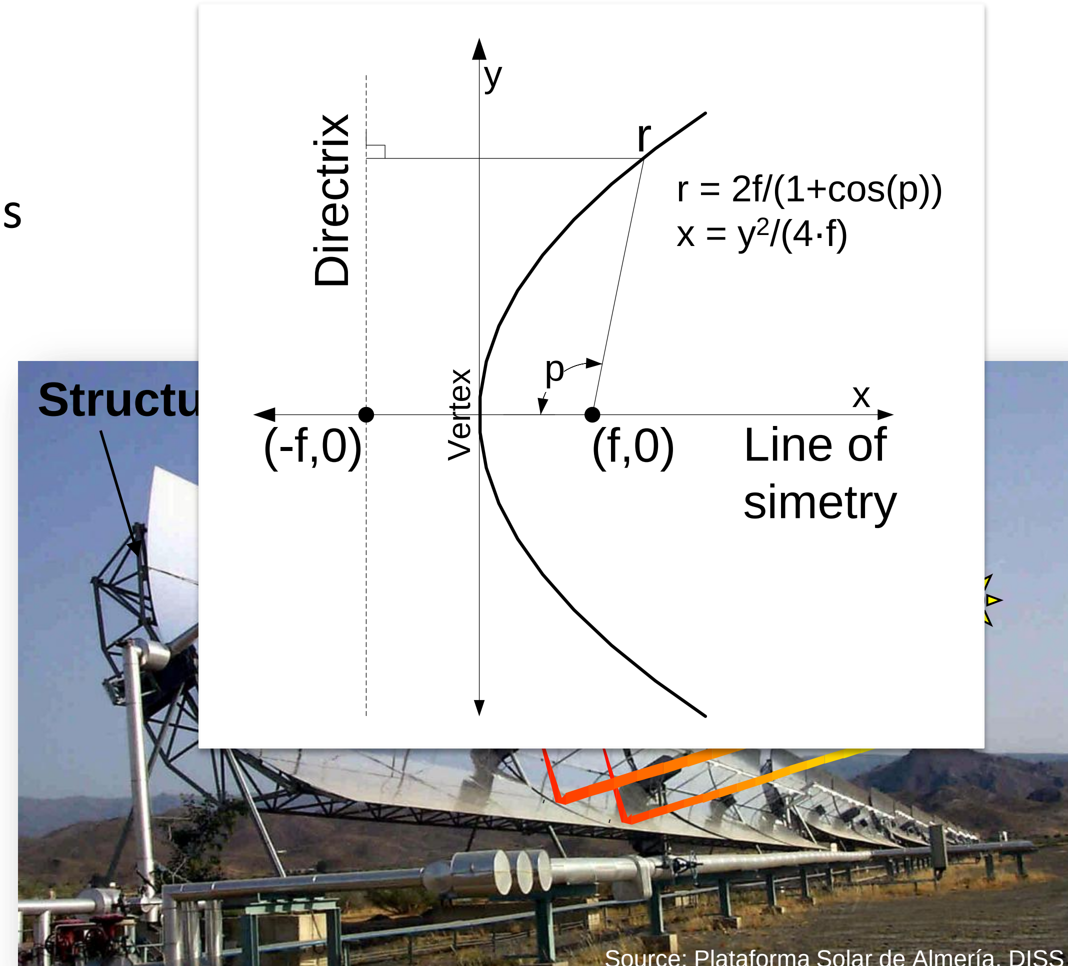
Contents

- Basic principles in parabolic-trough collectors technology
  - Main components
  - Energy balance: simplified analysis
  - Seasonal dependence of thermal energy production
- Configuration of STE plants with PTCs (oil based technology)
  - STE Plants without Thermal Energy Storage (TES) system (SEGs-type plant)
  - STE Plants with TES system (ANDASOL-type plant)
  - Solar fields integrated in Combined Cycle Systems (ISCCS) (KURAYMAT-type plant)

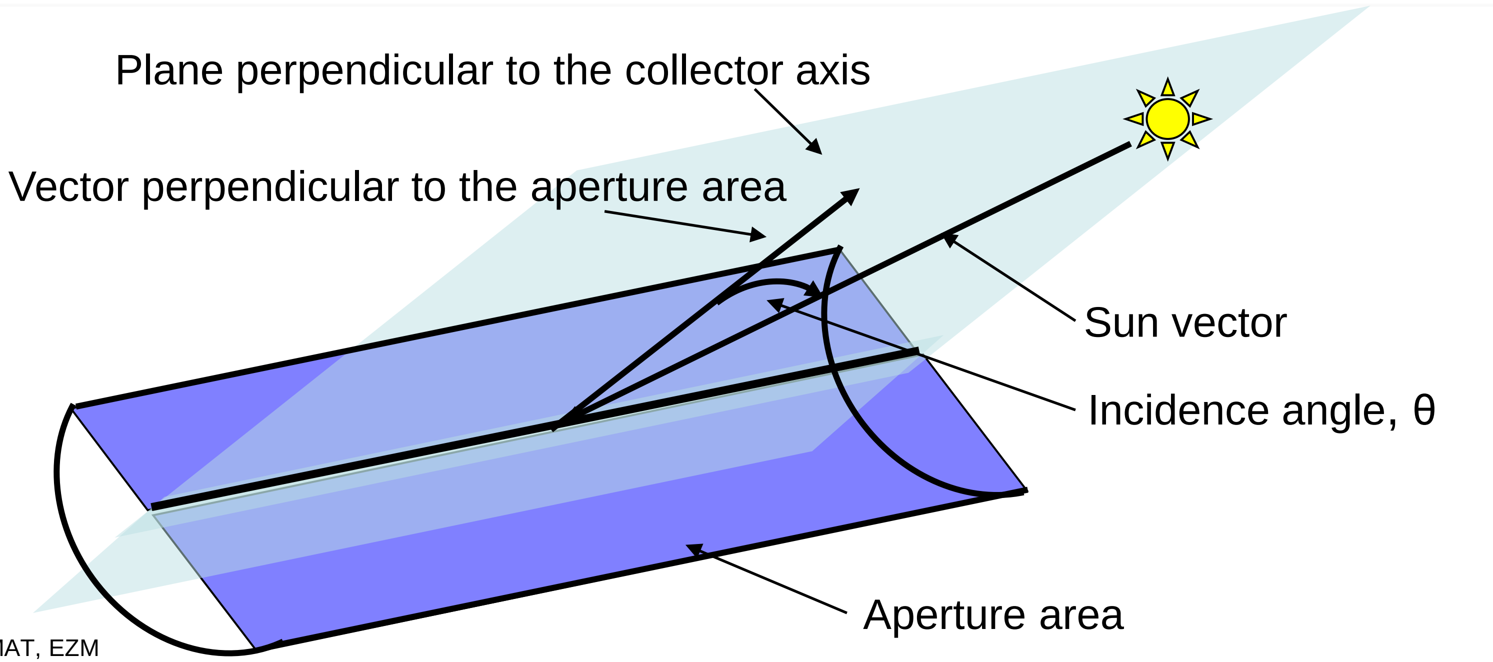
Elements:

- Trough collector (single-axis tracking)
- Reflectors
- Receivers (Heat-Collection Elements)
- Drive system, tracking system, pylons



How does a PTC work?

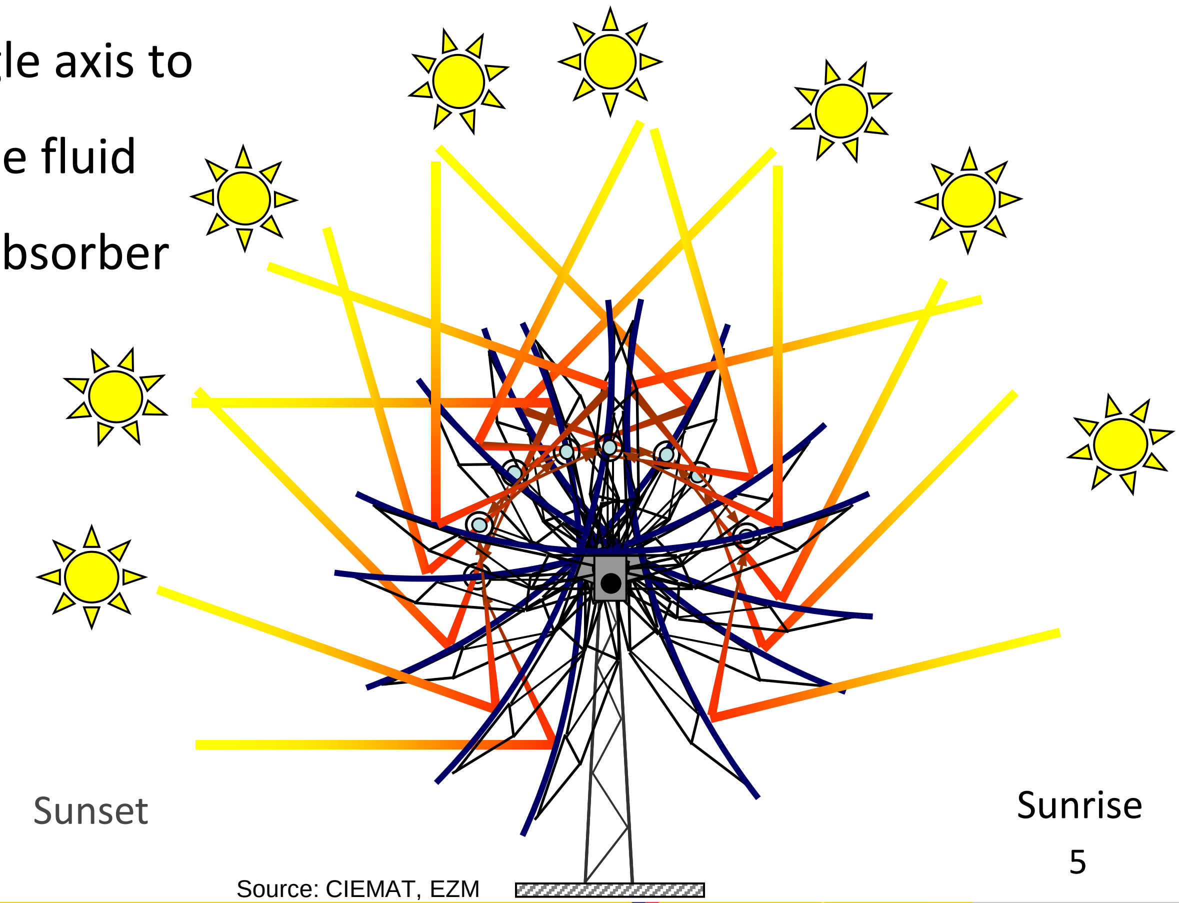
- It is positioned to guarantee the aperture plane is perpendicular to the plane containing the sun vector



Source: CIEMAT, EZM

How does a PTC work?

- It tracks the sun in a single axis to transfer the energy to the fluid circulating through the absorber pipe (HCE)



Source: CIEMAT, EZM

Elements:
Structure and reflectors

- In charge of concentrating solar radiation
- Reflectors:
  - most current designs use back-silvered glass mirrors
  - barriers for polished aluminum mirrors→ reflectance and durability

Torque-box structure-type EuroTrough (ET) collector

ET-type PTC with FLABEG RP3 glass mirrors

(Focal length = 1710 mm; Thickness = 4 mm; Dimensions = 1700x1501 mm^2(outer) /1700x1641 mm^2(inner))

Structure and reflectors:
Basic parameters

- **Reflectance (ρ):**
  - fraction of incident energy (solar radiation) reflected by a surface
  - depends on wavelength, direction and nature of the incident radiation, surface finish and surface temperature
  - typical solar hemispherical reflectivity glass-silver mirrors ~ 93%
- **Intercept factor (γ):**
  - ratio of the energy intercepted by the receiver to the energy reflected by the parabolic trough reflector
  - typical values in commercial mirrors > 98%

Elements:
Receivers (Heat Collection Elements)

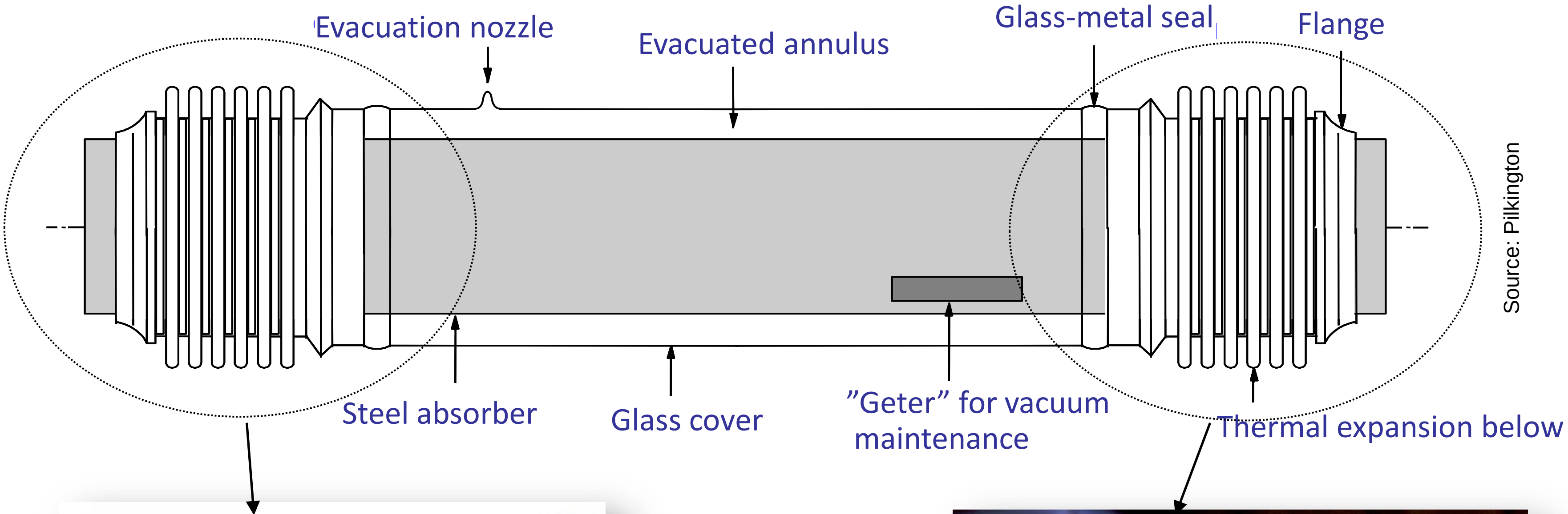
Composed by:

- Absorber pipe: Steel pipe with an external coating that:
  - Increases absorptance of solar radiation
  - Minimizes thermal losses
- Glass cover: Borosilicate glass cover with an antireflective coating to increase solar transmittance

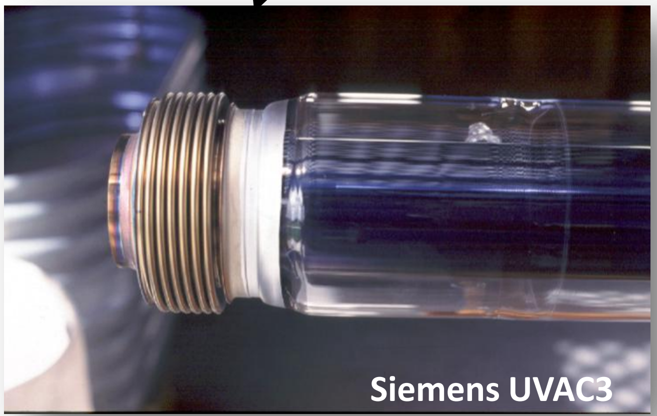
Characteristics:

- Vacuum in the annular cavity
- Getters for absorbing hydrogen and improve vacuum lifetime
- Glass-to-metal seal

Receivers:
Design characteristics




Schott PTR70

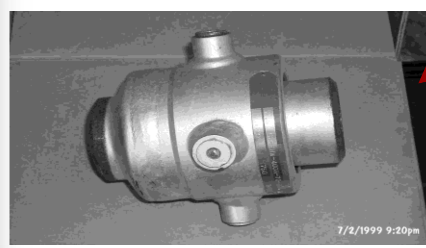

Siemens UVAC3

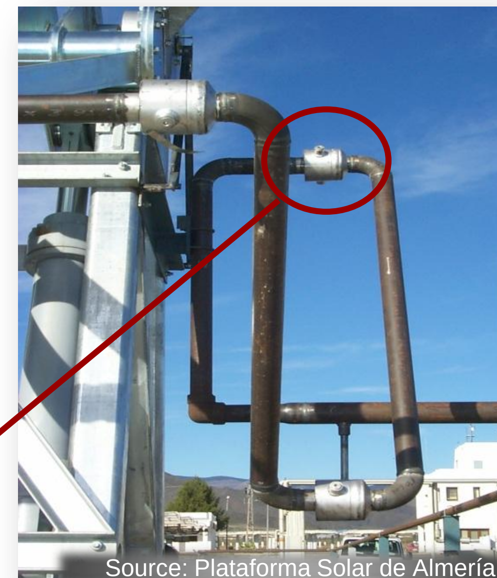
Receivers:
Optical and thermal parameters

- **Absorptance (α):**
  - fraction of incident energy (solar radiation) absorbed by a surface
  - depends on wavelength, direction of the incident radiation, surface finish and surface temperature
  - maximum solar absorptance values ~ 95%
- **Thermal emittance (ε):**
  - amount of energy emitted in all spatial directions by an area at a given temperature (T)
  - current values ≤ 14% @400°C
- **Transmittance (τ):**
  - fraction of incident energy (solar radiation) transmitted by the glass cover
  - maximum solar transmittance values ~ 96%

Elements: Flexible connections

- To connect single PTCs to the headers or PTCs to each other are used:
  - Flexible hoses: High pressure drop, stainless steel bellows, and limited flexibility for high temperature
  - Ball joints: provided with inner graphite sealing to reduce friction and avoid leaks





Ball joint

Elements:
Drives & Tracking systems

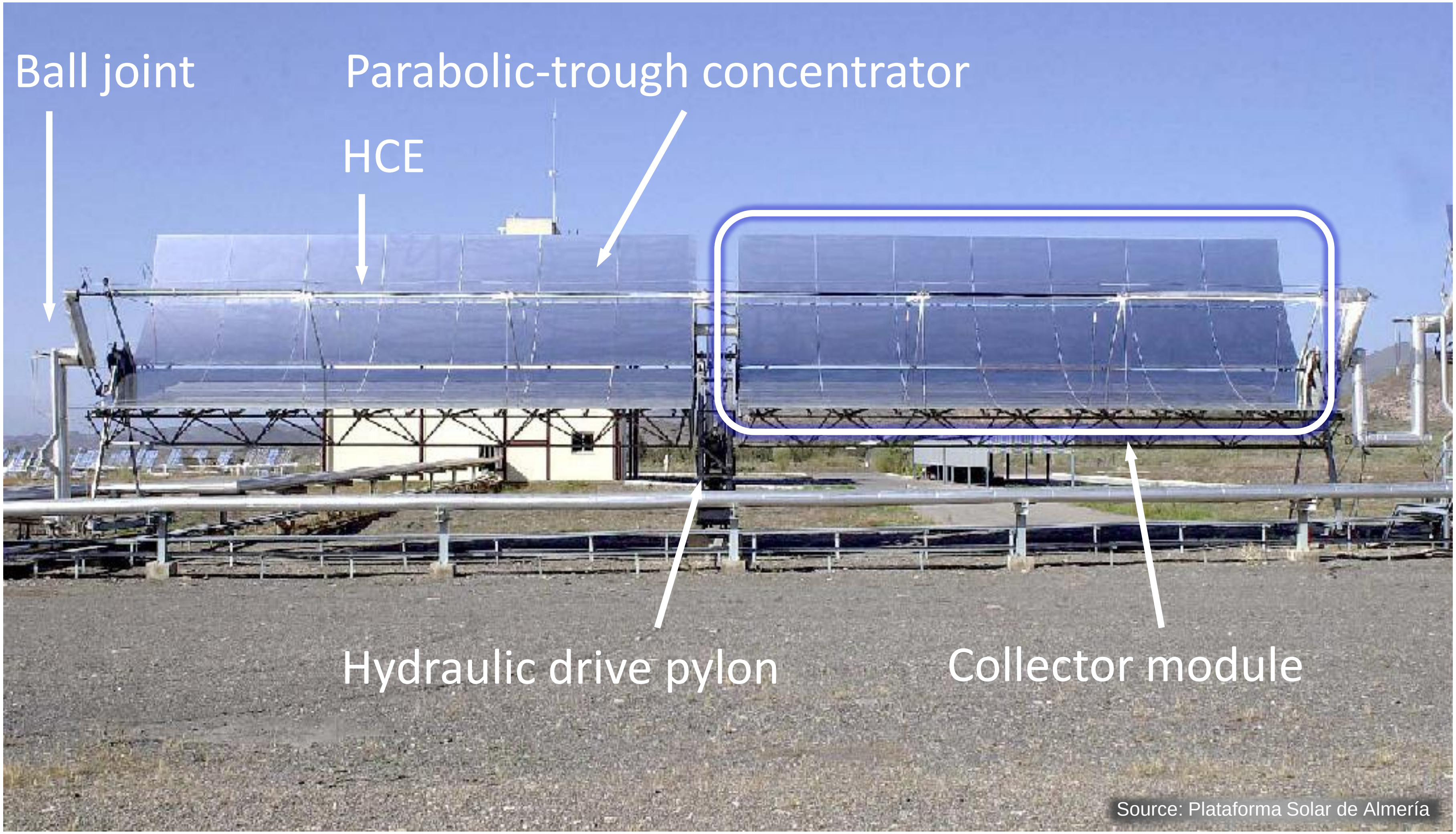
Hydraulic drive system

Tracking system: Light-sensing or intelligent tracker

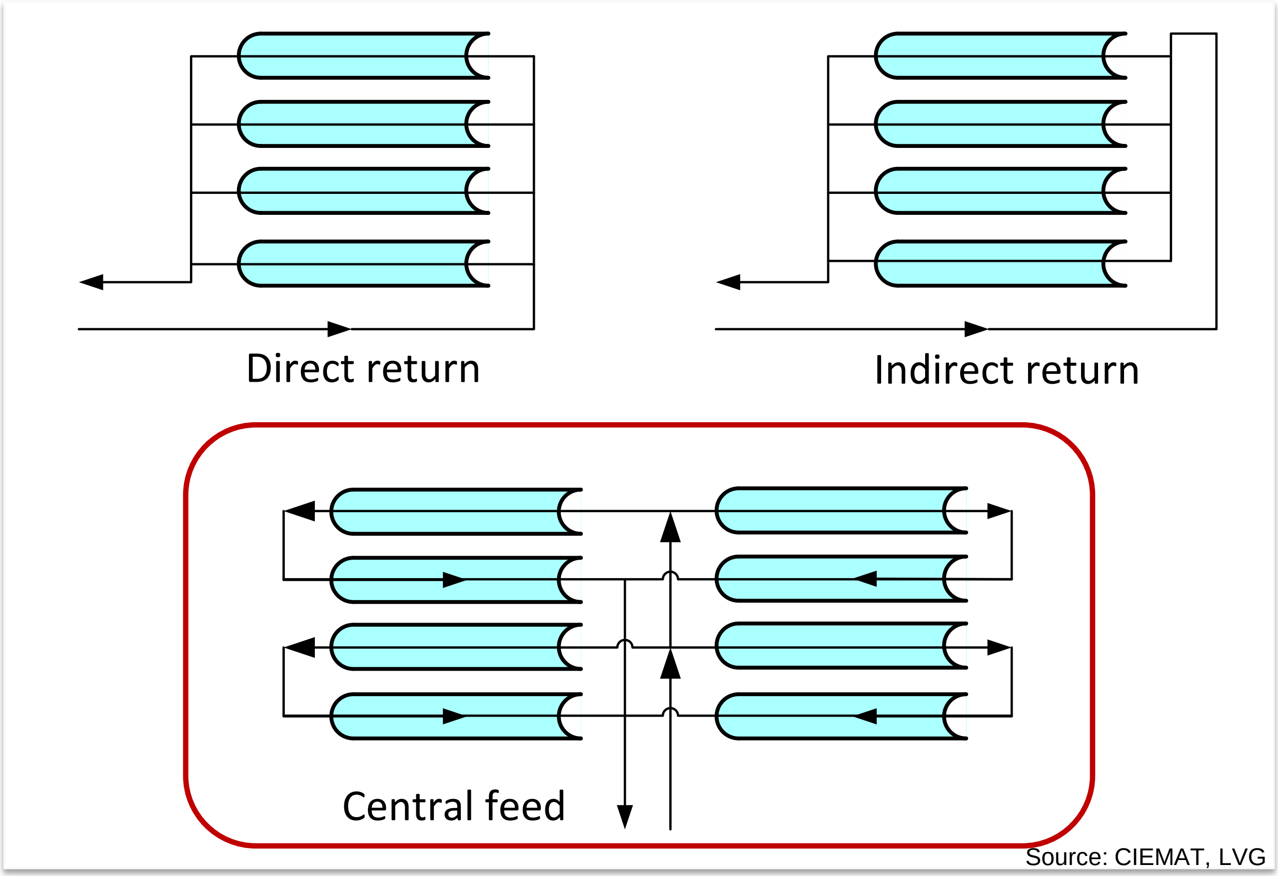
Heat transfer fluids in PTCs

- Mineral or synthetic oils
  - Therminol VP-1 (Solutia) / Dow A (Dow Chemical) (@400°C)
- Water:
  - Pressurized hot water
  - Direct steam generation (@500°C)
- Other proposals (Feasibility?):
  - Molten salts in parabolic trough collectors
  - Pressurized gasses

Parabolic-trough collector:
View of a collector unit

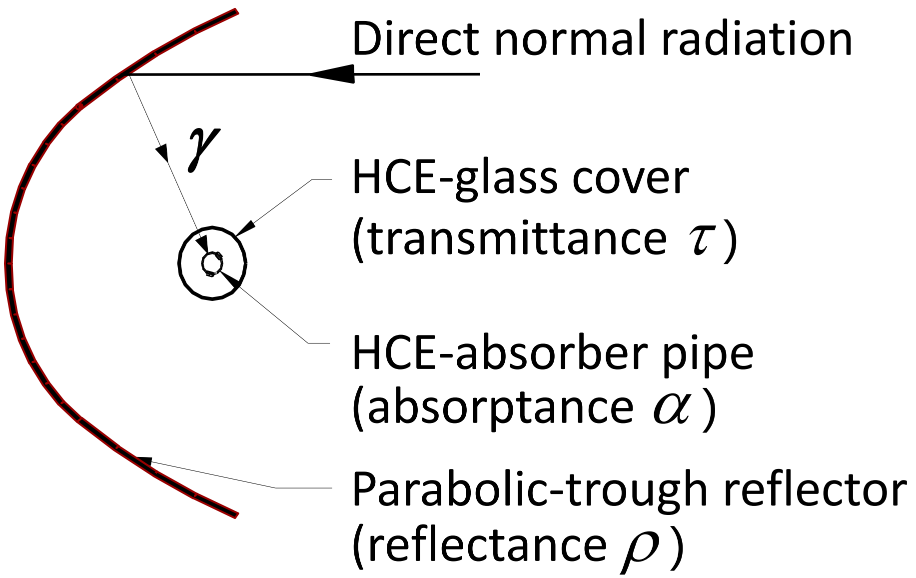


Parabolic-trough collectors:
Solar field configurations



- Type of losses in PTCs:
  - Optical losses
  - Geometrical losses
  - Thermal losses

Parabolic-trough collectors: performance parameters



Source: CIEMAT, EZM

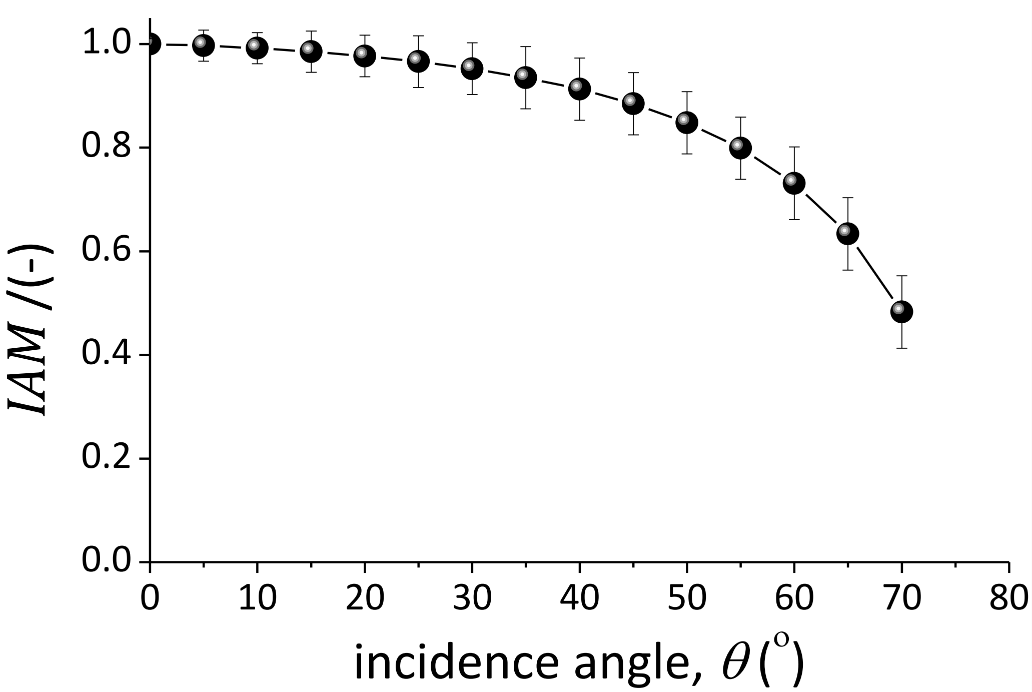
- Optical efficiency (η_o)
  - ratio of the radiant power absorbed by the receiver to the useful radiant solar power at the collector
- Peak-optical efficiency ($\eta_{o,peak}$)
  - optical efficiency when the incidence angle is zero (= direct solar radiation is perpendicular to the collector aperture plane)

$$\eta_{o,peak} = \rho * \gamma * \tau * \alpha = \eta_{o,\theta=0°}$$

$$\eta_o = \eta_{o,\theta\neq0°} = \eta_{o,\theta=0°} * IAM$$

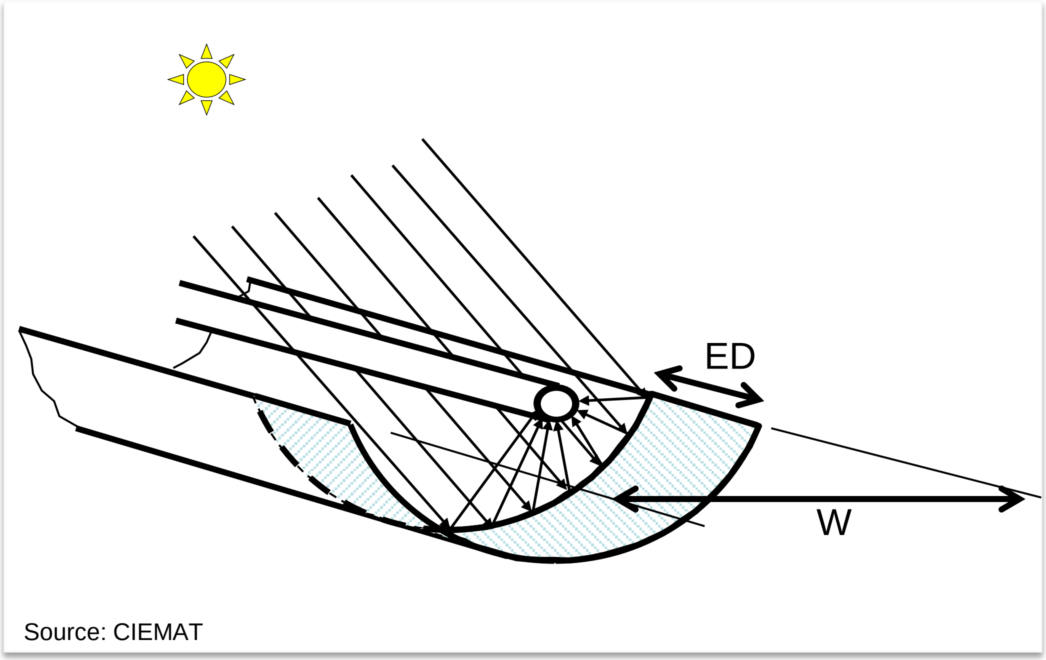
Incidence angle modifier (IAM)

- Performance factor that:
  - includes the change of optical and geometrical parameters when incidence angle is not 0°
  - does not include the cosine effect
  - changes from 0 to 1 (a value of 1 occurs when θ = 0°)

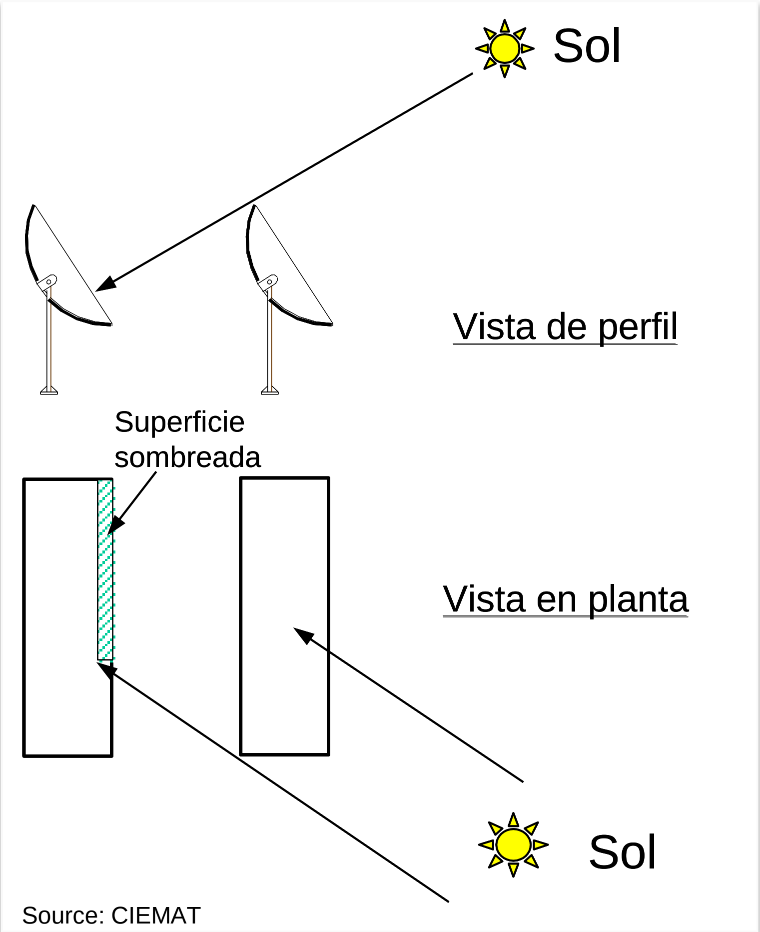


Source: CIEMAT, LVG

Geometrical losses

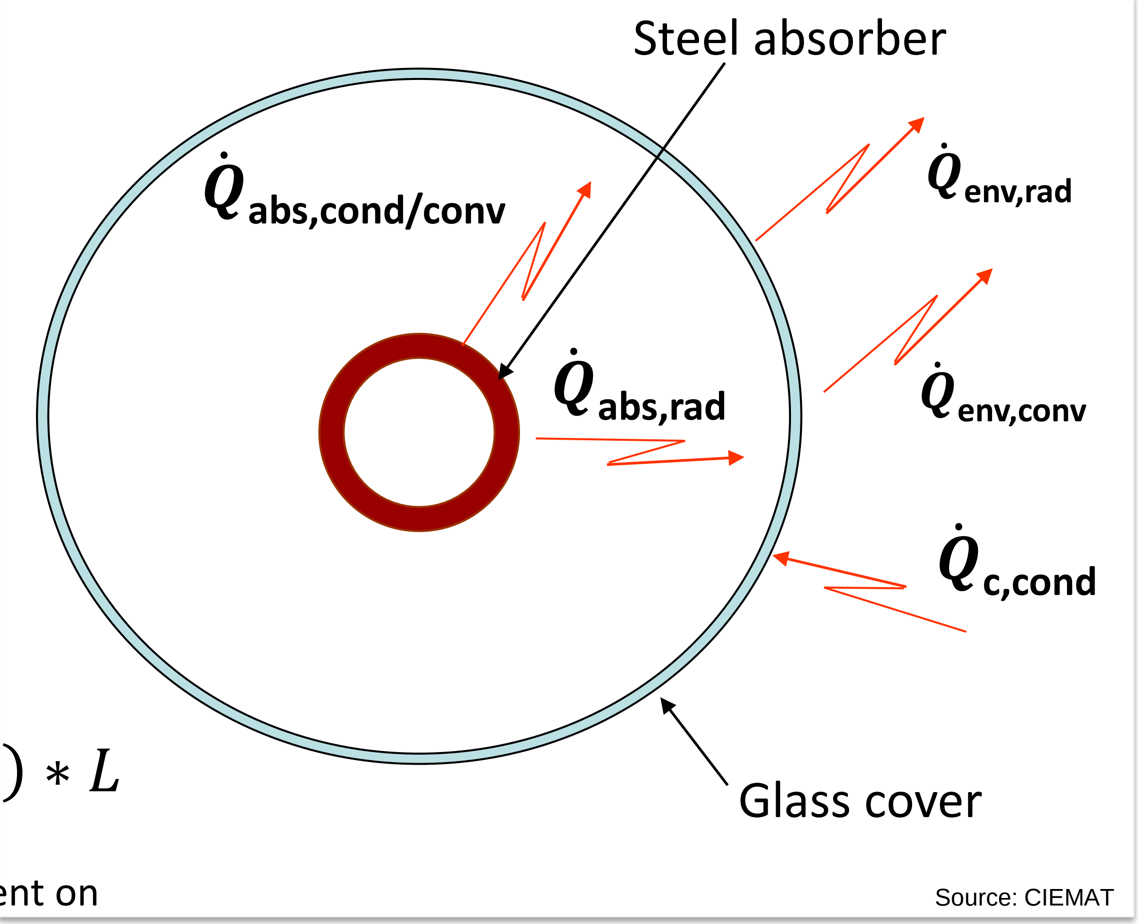


Collector geometrical end losses



Shadows between adjacent rows

Heat losses

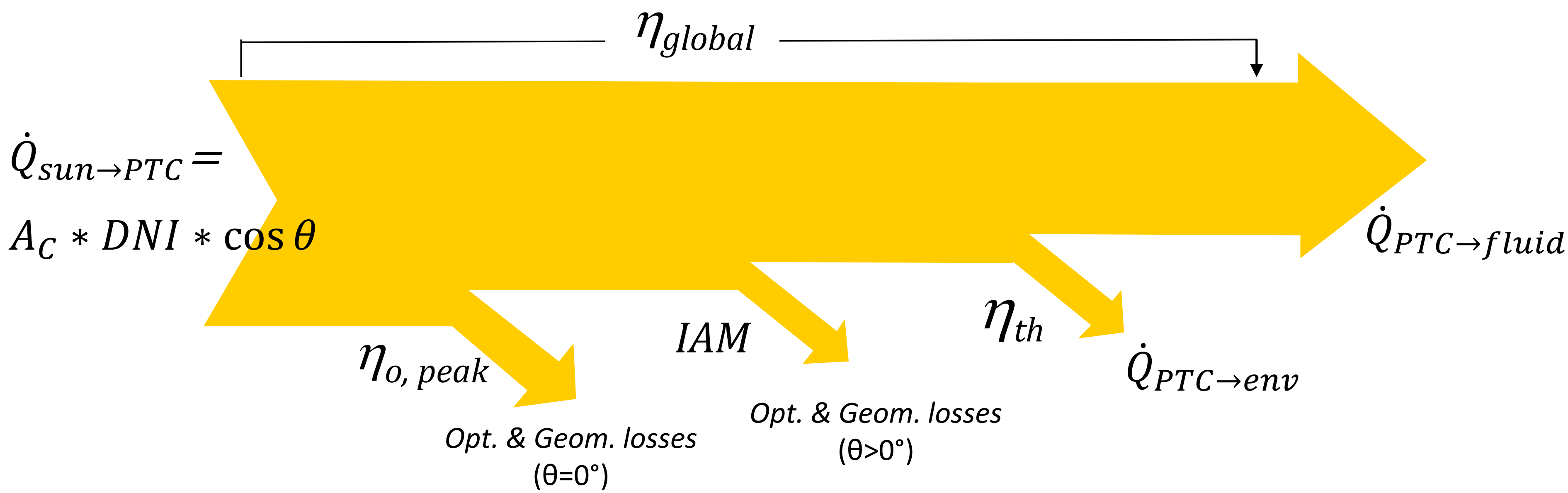


$$\dot{Q}_{PTC\rightarrow env} = H_l(T_{abs}, T_{env}) * L$$

H_l Thermal-losses function dependent on absorber and environmental temp. (W/m)

L Absorber-pipe length (m)

Parabolic-trough Collectors:
Energy balance



$$\dot{Q}_{PTC \rightarrow fluid} = \boxed{A_C * DNI * \cos\theta} \boxed{* \ \eta_{o,peak}} \boxed{* \ IAM} \boxed{* \ F_c} \boxed{- \ \dot{Q}_{PTC \rightarrow env}}$$

- Thermal losses in EuroTrough prototype (PSA) with Schott receivers:

$$\dot{Q}_{PTC \rightarrow env} = \Bigg(0.00154 * \Delta T^2 + 0.2021 * \Delta T - 24.899 + \left((0.00036 * \Delta T^2 + 0.2029 * \Delta T + 24.899) * \left(\frac{DNI}{900}\right) * \cos\theta\right)\Bigg) * L$$

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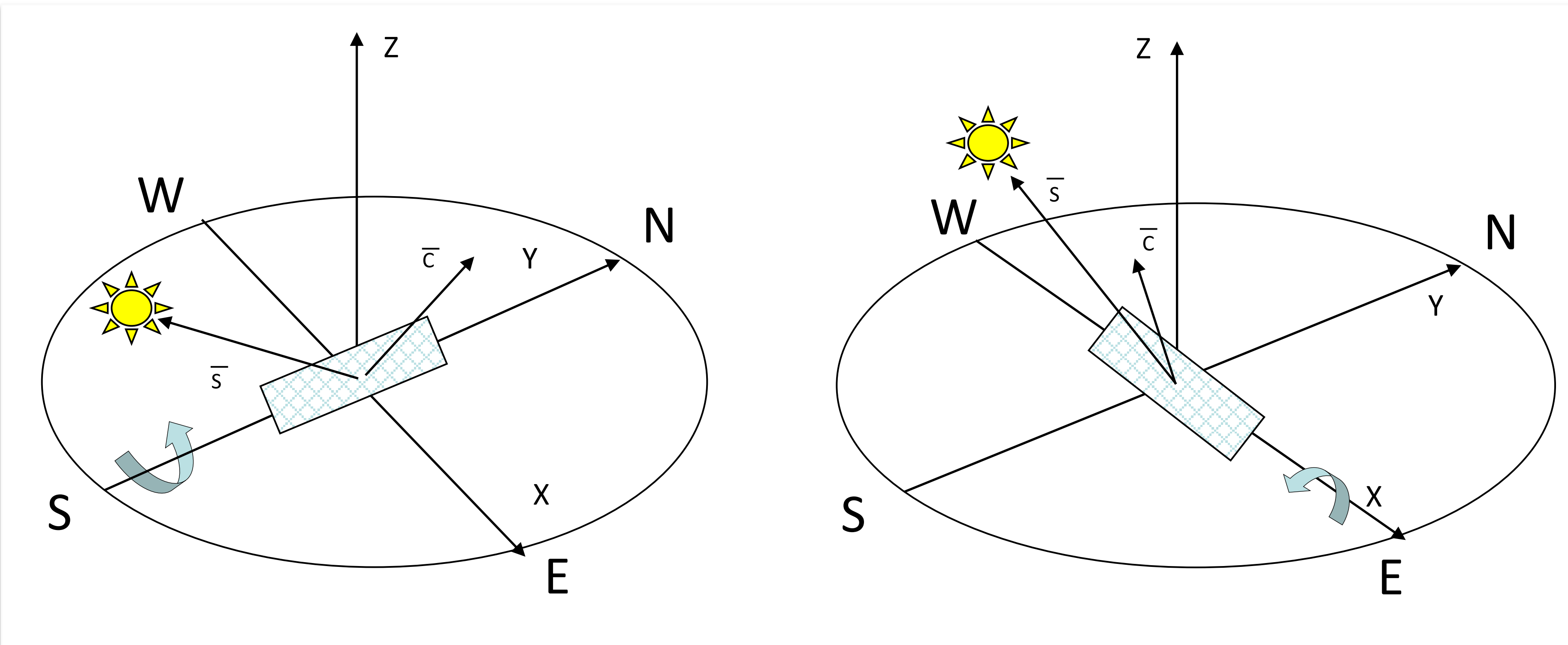
STE Plants with PTC:
Seasonal dependence of energy production

- Thermal energy produced by a solar field with PTCs whose axis is North-South oriented varies a lot during the year. Three to four times more energy is delivered daily during summer months than in winter months. Thermal energy delivered by PTCs with axis oriented east-west does not vary as much from summer to winter.

STE Plants with PTC:
Seasonal dependence of energy production

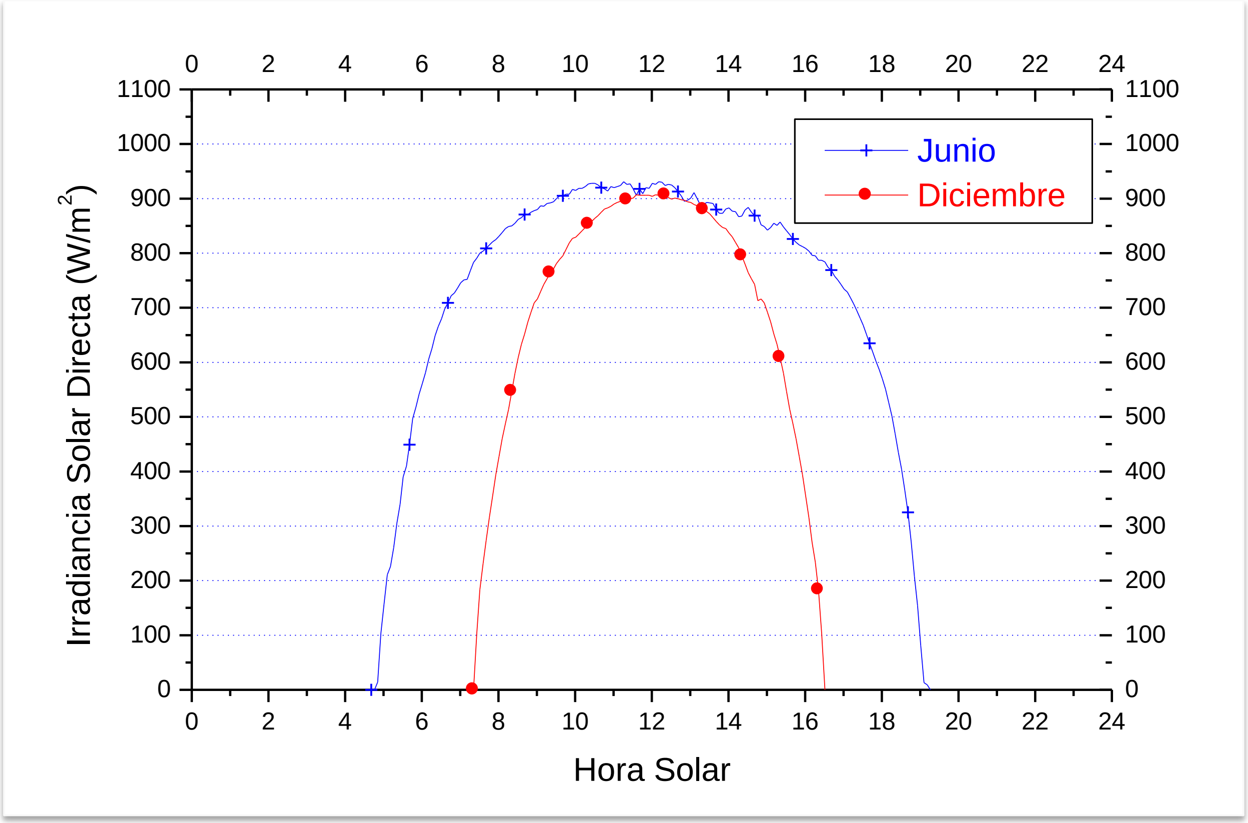


Source: CIEMAT

a) Axis oriented North-South
Tracking East-West

b) Axis oriented East-West
Tracking North-South

STE Plants with PTC:
Seasonal dependence of energy production



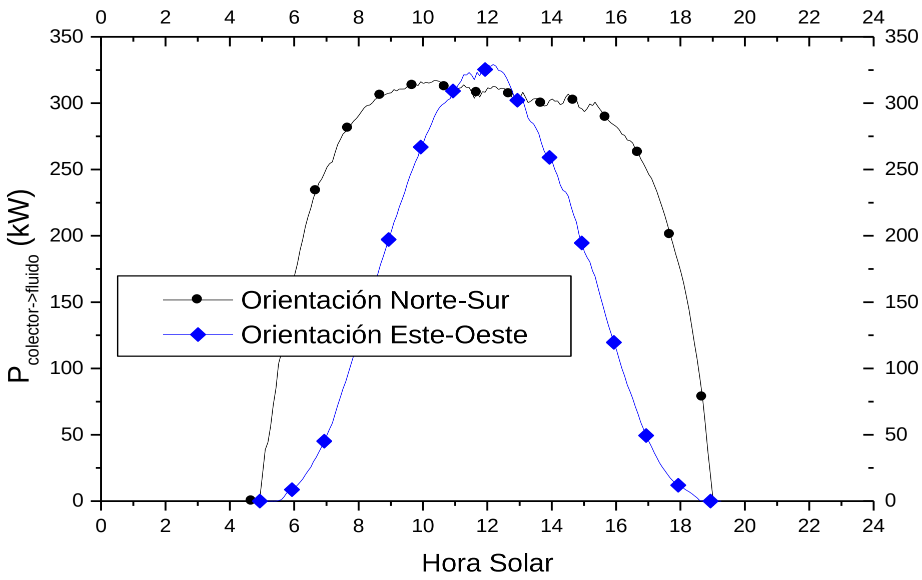
Typical daily DNI profile in June and December (PSA)

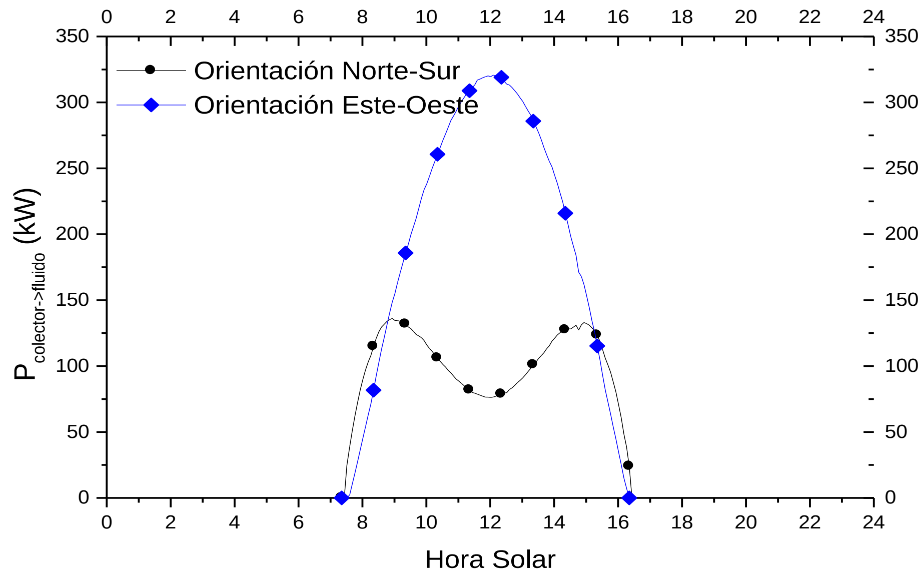
STE Plants with PTC:
Seasonal dependence of energy production

Influence of the axis orientation in the seasonal behaviour

ET-100 thermal power (kW)

Simulation of the behavior of a ET-100 PTC-type located at the PSA





Source: CIEMAT, EZM

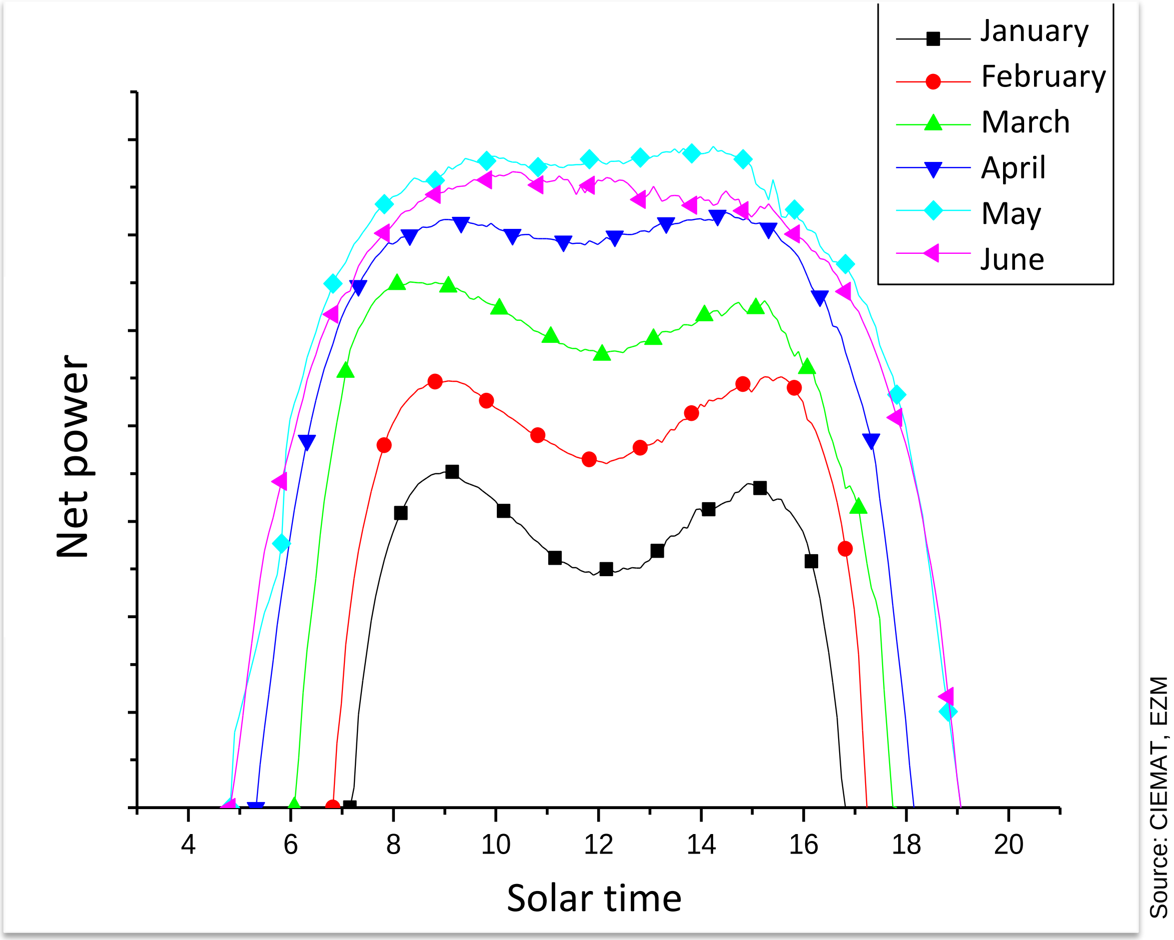
Sunny day in June

Sunny day in December

STE Plants with PTC:
Seasonal dependence of energy production

- Thermal energy produced by a solar field with PTCs whose axis is North-South oriented varies a lot during the year. Three to four times more energy is delivered daily during summer months than in winter months. Thermal energy delivered by PTCs with axis oriented East-West does not vary as much from summer to winter.
- The yearly thermal energy output of a North-South-type solar field is greater than the output of a East-West-type solar field .

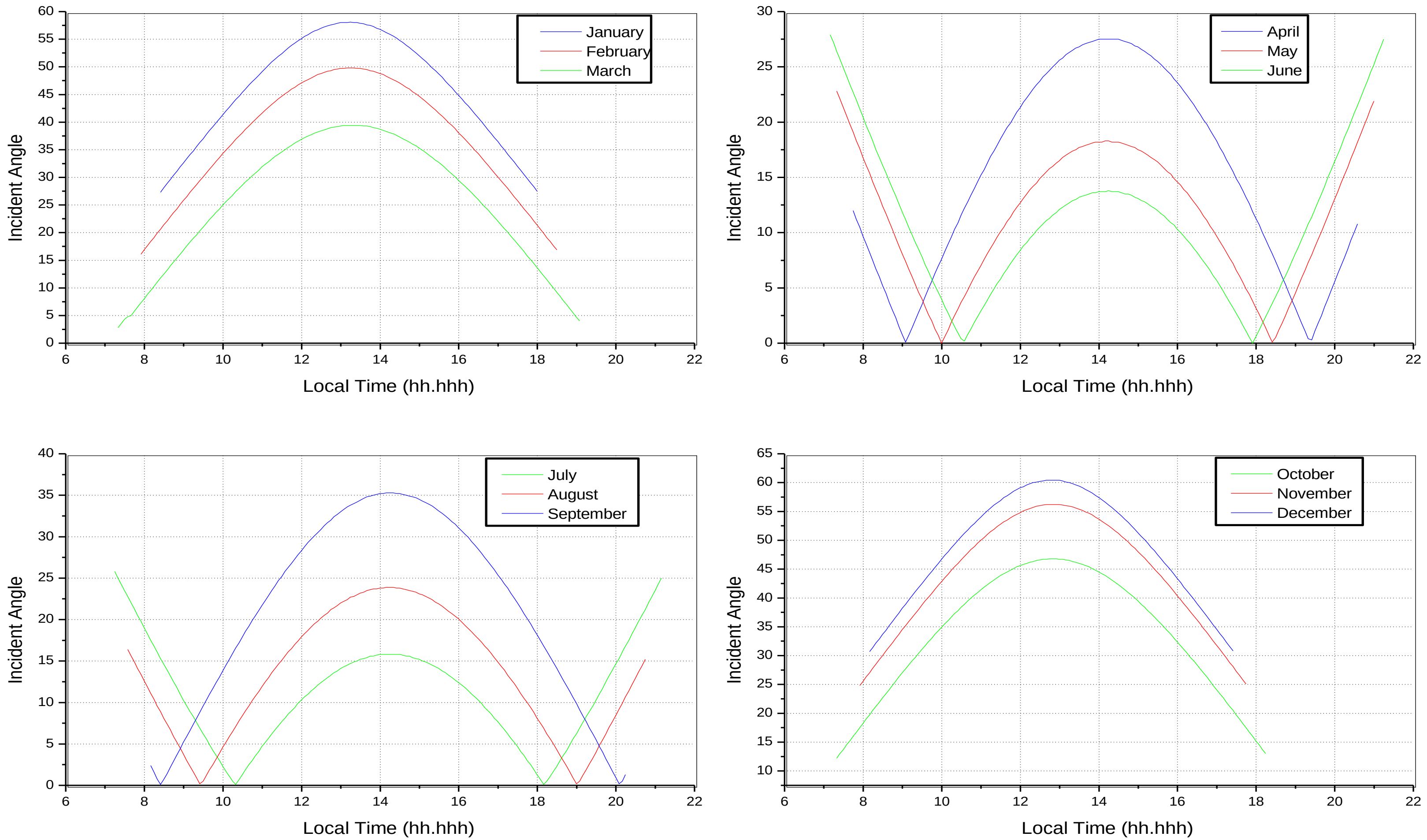
STE Plants with PTC:
Seasonal dependence of energy production



Daily profile of the net power delivered to the grid by a PTC solar field (North-South oriented)

STE Plants with PTC:
Seasonal dependence of energy production

Daily profile of incidence angle in PTCs with axis oriented North-South (PSA coordinates)

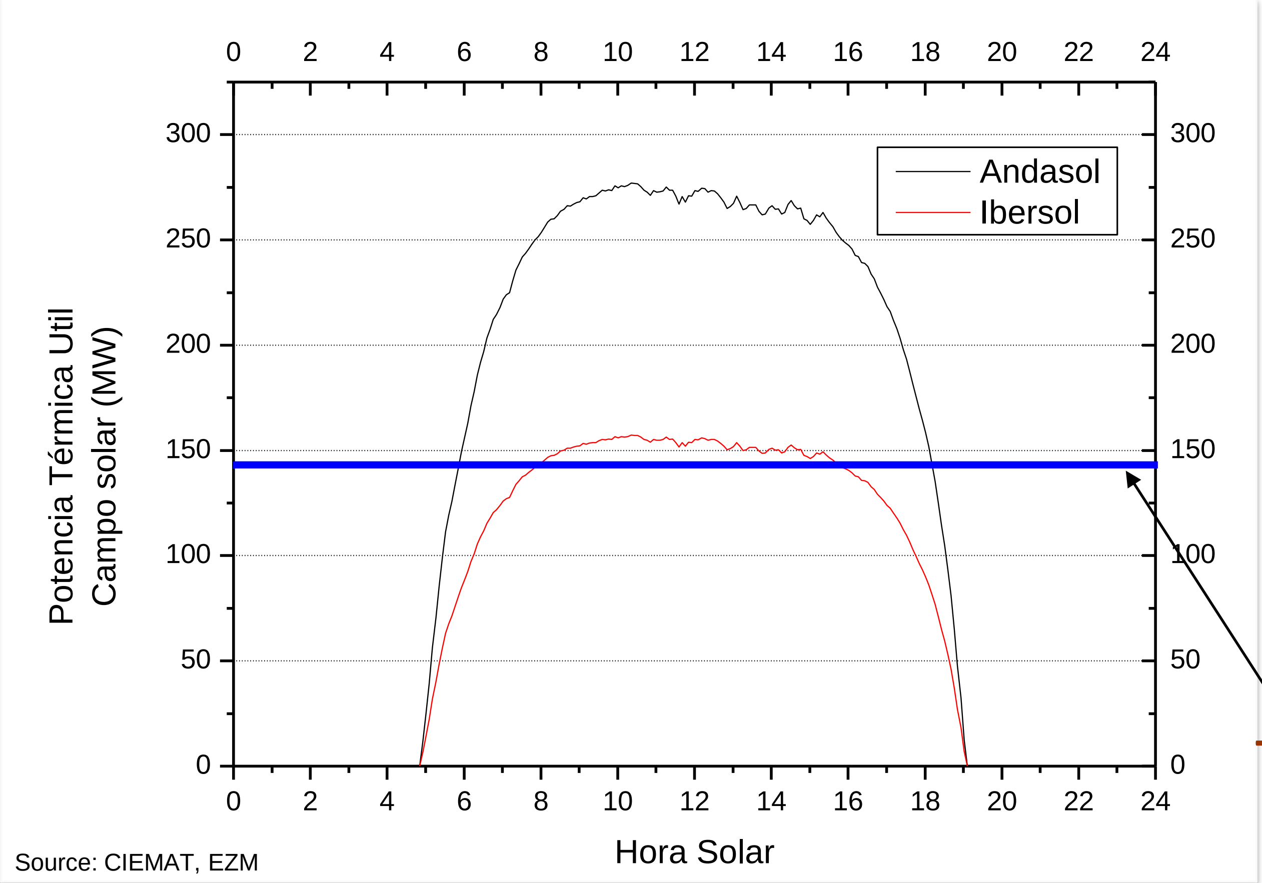


Source: CIEMAT, EZM

STE Plants with PTC:
Seasonal dependence of energy production

- Thermal energy produced by a solar field with PTCs whose axis is North-South oriented varies a lot during the year. Three to four times more energy is delivered daily during summer months than in winter months. Thermal energy delivered by PTCs with axis oriented East-West does not vary as much from summer to winter.
- The yearly thermal energy output of a North-South-type solar field is greater than the output of a East-West-type solar field .
- The size of the solar field depends on the nominal electric power of the STE plant but also on the existence or not of a thermal energy storage (TES) system and on its capacity.

Thermal power produced (calculated) by Andasol-I and Ibersol solar fields (sunny day in June)



Andasol-I:

- 50 MWe nominal electric power
- 510000 m^2 of PTCs (155 collector loops; 4 PTCs per loop)
- Thermal storage 1000 MWh

Ibersol:

- 50 MWe nominal electric power
- 288000 m2 of PTCs (88 collecor loops; 4 PTCs per loop)
- NO thermal storage system

Thermal power required by the power block (50 MWe)

STE Plants with PTC:
Seasonal dependence of energy production

- Thermal energy produced by a solar field with PTCs whose axes are North-South oriented varies a lot during the year. Three to four times more energy is delivered daily during summer months than in winter months. Thermal energy delivered by PTCs with axis oriented East-West does not vary as much from summer to winter.
- The yearly thermal energy output of a North-South-type solar field is greater than the output of a East-West-type solar field .
- The size of the solar field depends on the nominal electric power of the STE plant but also on the existence or not of a thermal energy storage (TES) system and on its capacity.
- A TES system with capacity to guarantee 2 to 3 hours of power plant operation at nominal power is an excellent help to fulfill the requirements of the electricity transmission grid manager, specially during partly cloudy days.

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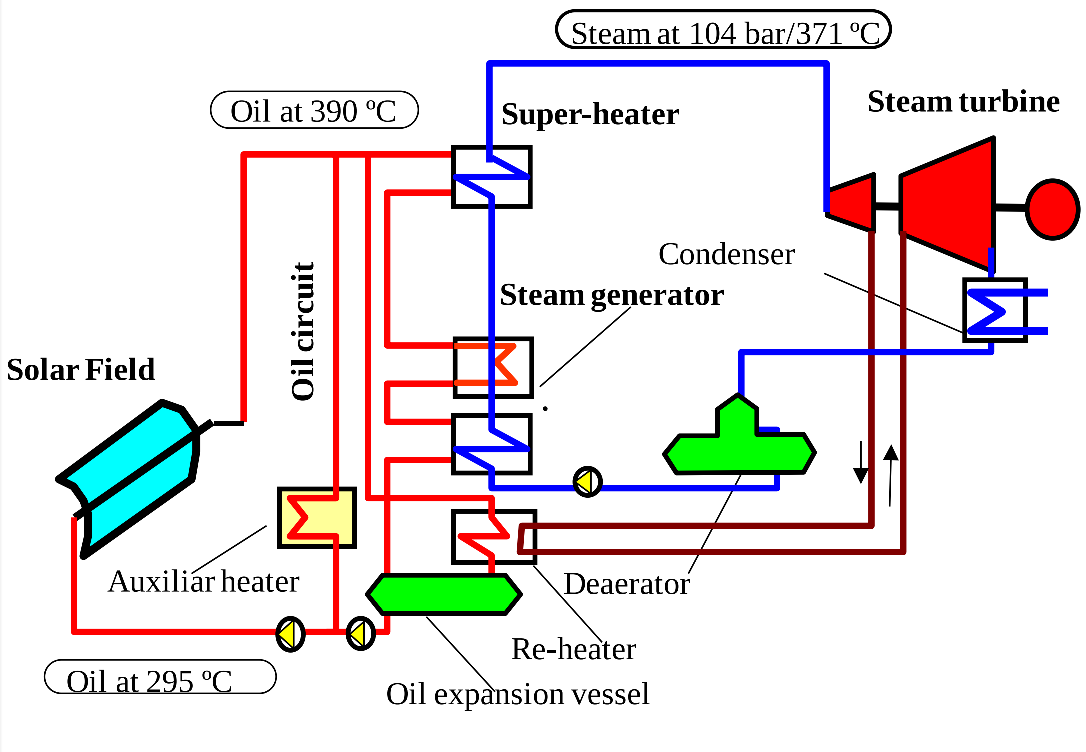
STE Plants without TES system: SEGS-type plant

- Solar field with PTCs supplying thermal energy to the steam generator of a Rankine cycle (unfired boiler steam generator)
- HTF fluid: Thermal oil
- Solar field coupled to the steam boiler, superheater and/or reheater
- Medium grid stability (Hybridization with fossil fuel - solar field or steam boiler)



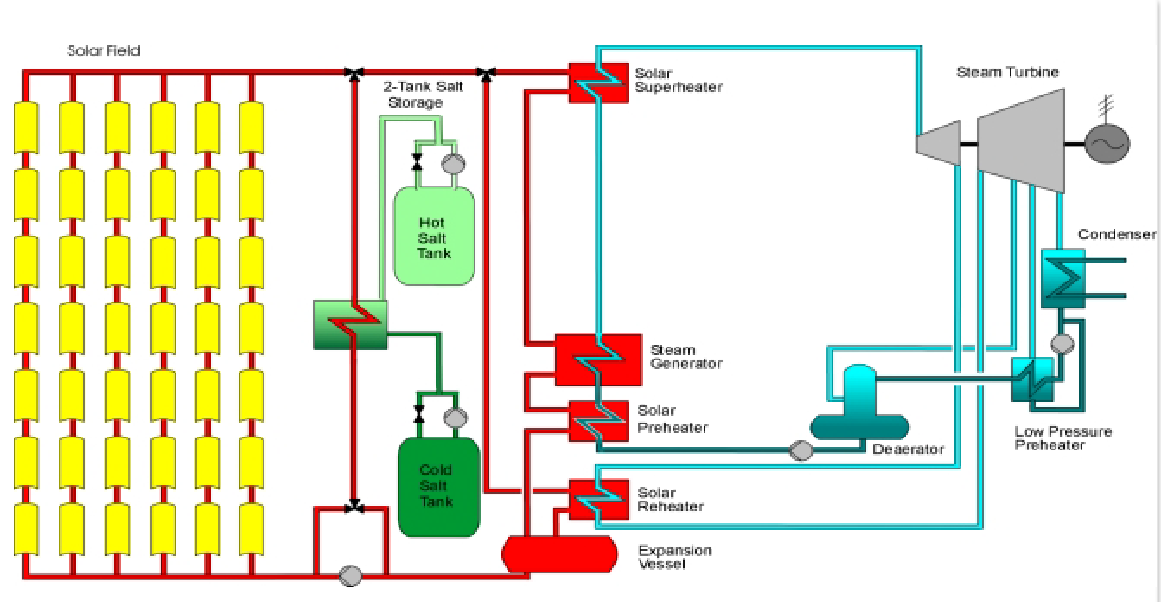
Source: CIEMAT, EZM

Scheme of SEGS VIII & SEGS IX STE Plants

- Reheat regenerative steam power cycle (steam cycle efficiency ~ 37.6%)
- Nominal electric power = 80MWe (solar to electricity annual efficiency ~ 13.6%)
- SEGS-I to SEGS-IX built by the Luz Company of United States between 1985 and 1991

STE Plants with TES system: ANDASOL-type plant

- PTCs solar field supplying thermal energy to the SG of a Rankine cycle and to a TES system
- High grid stability
- Standard configuration:
  - Oil based technology
  - 2-Tank molten salt TES system
  - Central feed configuration for the solar fields (> 500,000 m^2 of mirror surface for 50 MWe and 7,5 h TES capacity-Spanish STE plants)



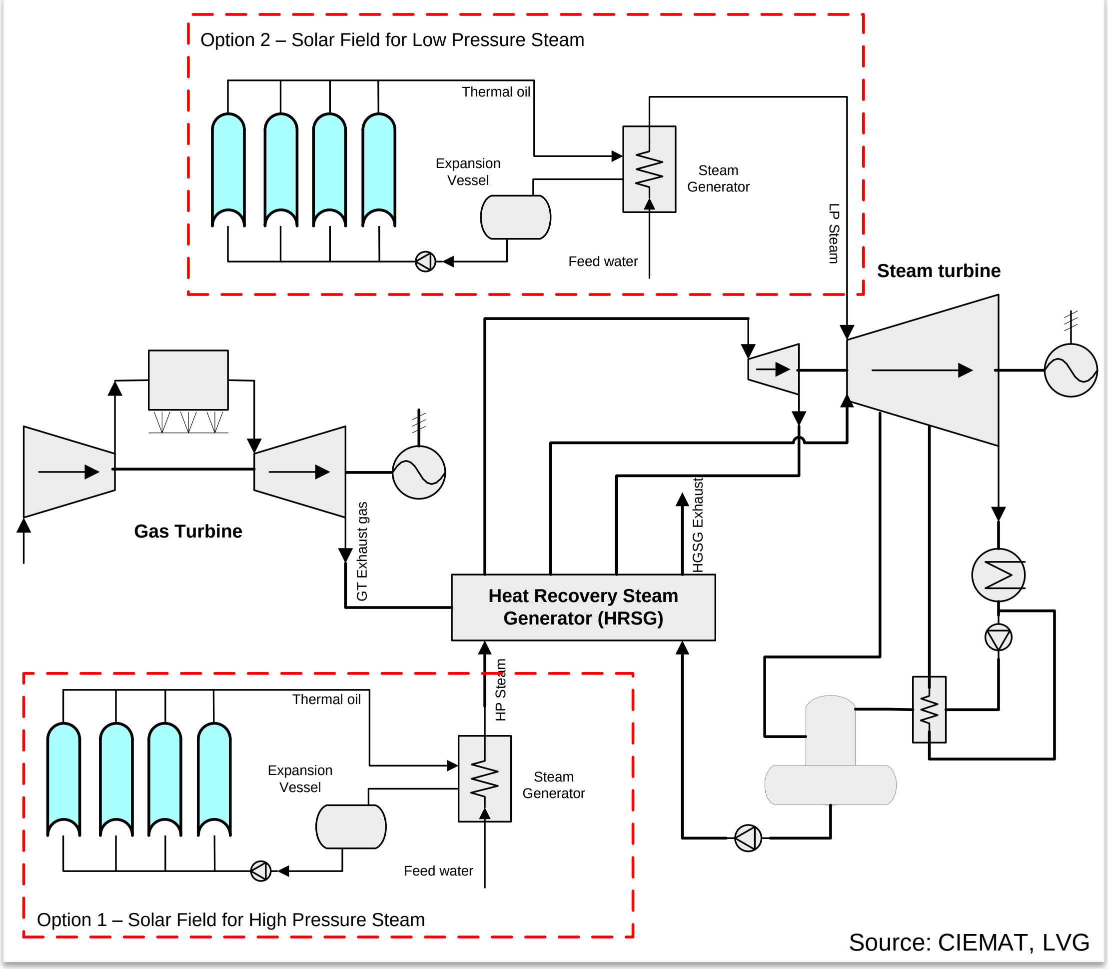
Source: Solar Millenium AG

Scheme of Andasol-type STE Plants

- Reheat regenerative steam power cycle (steam cycle efficiency ~ 37.5%)
- Nominal electric power = 49.9 MWe
- TES system:
  - Storage medium: Nitrate salt mixture (60% $NaNO_3$ – 40% KNO_3)
  - Capacity 7,7 h @ 50MW (28500 Tons of molten salts)
- Andasol power plants promoter: Solar Millenium AG
- Technology integrators involved in Andasol-I and Andasol-II: Flagsol GmbH, ACS Cobra, Sener,…

Integrated Solar Combined Cycle Systems: (ISCCS)

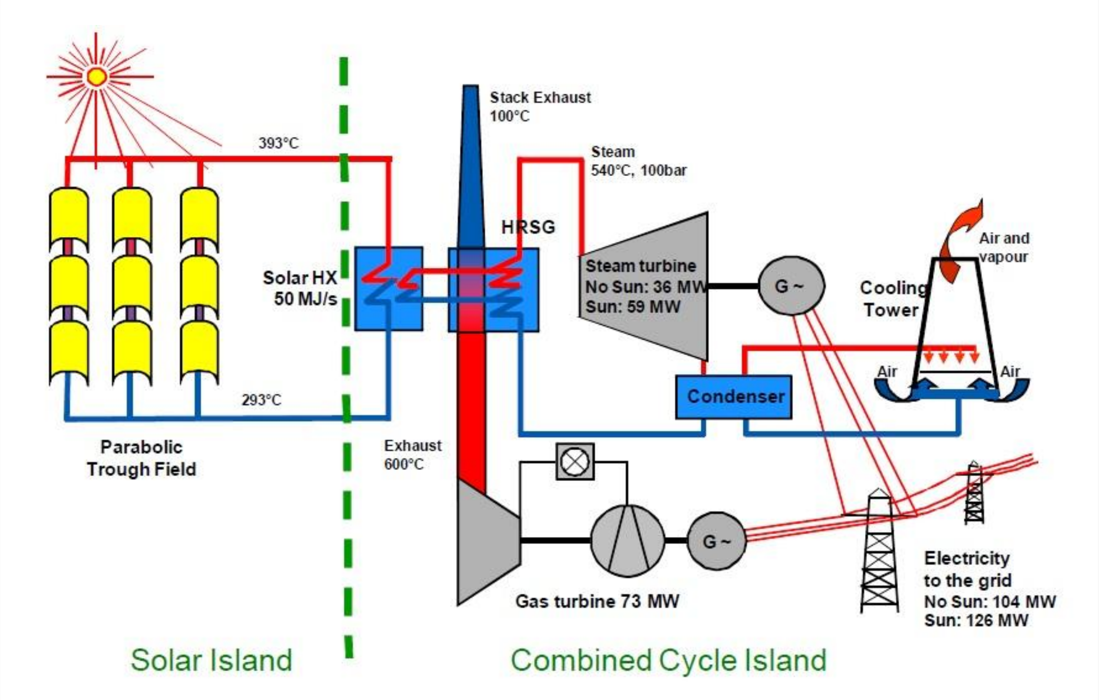
- Hybrid STE plant with PTCs making use of the ISCCS scheme
- The solar field is integrated in the bottoming cycle of a combined-cycle gas-fired power plant for:
  - High-Pressure Steam → HRSG → HP-stage of Steam Turbine (ST)
  - Low-Pressure Steam → LP-stage of ST



Integrated Solar Combined Cycle Systems: Kuraymat-type plant

- Hybrid STE plant with PTCs making use of the ISCCS scheme
- The solar field is integrated in the bottoming cycle of a combined-cycle gas-fired power plan for:
  - High-Pressure Steam → HRSG → HP-stage of Steam Turbine (ST) (Option 1) *

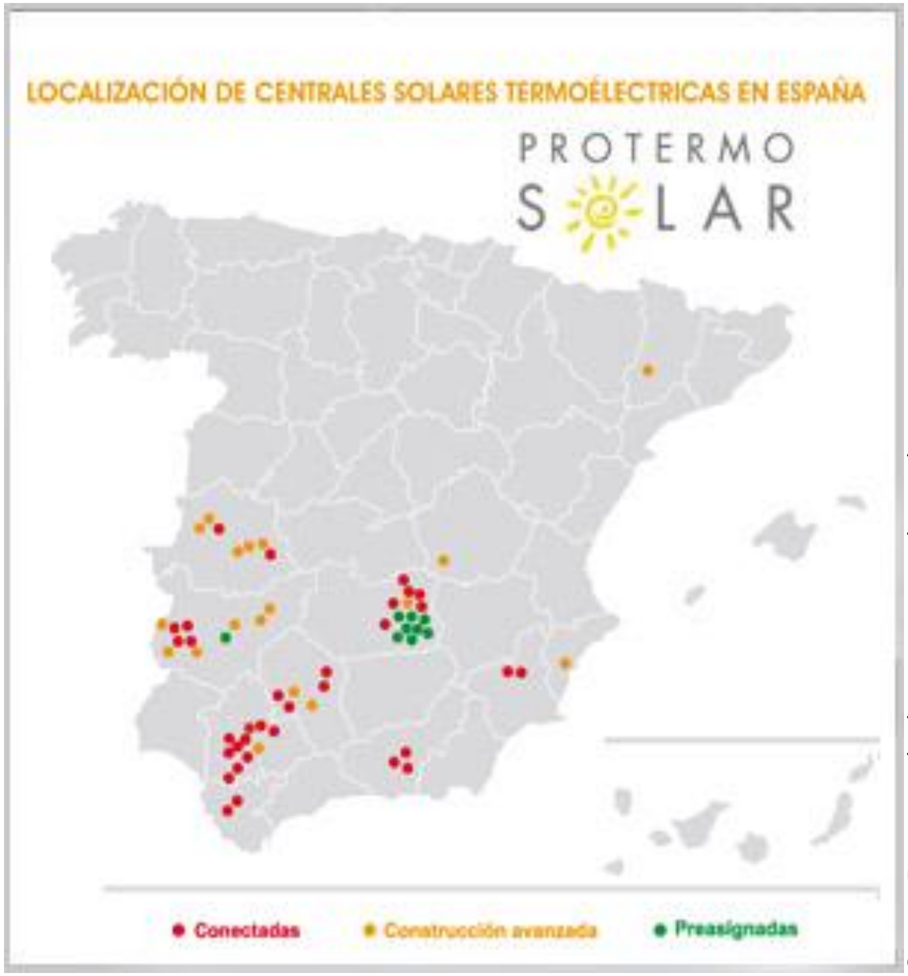
*Brackmann et al., Construction of the ISCCS Kuraymat, *SolarPACES2009*, Berlin, Germany.



Source: Fitchner Solar GmbH

STE plants with PTCs in Spain

- 35 STE plants connected to the grid:
  - 30 PTCs solar fields (14 with TES system)
  - 1500 MW_e of 1581 MW_e come from PTCs solar fields (oil based technology)
- 17 STE plants under construction:
  - 16 STE plants with PTC solar fields
- Standard configuration of STE plants with PTCs solar fields:
  - Nominal power: 50 MW_e
  - TES system capacity: 7,5 h@ 50 MW_e
- Large part of key CSP players are Spanish companies:
  - Abengoa Solar, Acciona Energía, ACS Cobra, Sener, Torresol Energy, ...



Source: Protermosolar (www.protermosolar.com)

Date: June 24, 2012

Additional comments

- The SEGS experience was essential to explain what is happening today…
- STE plants with PTC has turned into reliable renewable energy power stations
- Spain has played a key role in the commercial development of the technology during the last five years (Spanish RD 661/2007)
- Dimensions and configuration of current PTCs are mainly imposed by:
  - A limited selection in reflectors and receivers for commercial application whose size are conditioned by basis configuration of the LS-3-type collector (installed in SEGS plants)
  - As a result, there are many similarities between PTCs currently installed in STE Plants
- Future developments of PTC technology for STE Plants involve new designs of PTCs (bigger sizes), the replacement of the heat transfer fluid in the solar field (DSG technology?), and new types of TES systems

Gracias

Thank you

Danke schön

Merci beaucoup

Geometrical end losses

Parabolic-trough Collectors:
Equations for incidence angle

- PTC axis oriented East-West:

$$\theta = \arccos\left(\sqrt{1 + \cos^2\delta \cdot (\cos^2\omega_s - 1)} \right)$$

- PTC axis oriented North-South:

$$\theta = \arccos\left(\cos\delta \cdot \sqrt{(\cos\lambda \cdot \cos\omega_s + \tan g\,\delta \cdot sen\lambda)^2 + sen^2\omega_s} \right)$$