



CLASE VI

PLANTAS TERMOSOLARES DE CONCENTRACIÓN (CSP)

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Septiembre 2024

<http://diarium.usal.es/termodinamica>



ESQUEMA

- 1 INTRODUCCIÓN. TIPOS DE CONCENTRADORES
- 2 PLANTA TERMOSOLAR PURA. MODELO TERMODINÁMICO
- 3 PLANTAS HÍBRIDAS TIPO BRAYTON



ESQUEMA

1 INTRODUCCIÓN. TIPOS DE CONCENTRADORES

- Funcionamiento
- Tipos de concentradores
- Esquemas de planta

2 PLANTA TERMOSOLAR PURA. MODELO TERMODINÁMICO

3 PLANTAS HÍBRIDAS TIPO BRAYTON

FUNCIONAMIENTO GENERAL

Energía termosolar

Energía solar

Calentar gas (aire)

Ciclo termo-
dinámico

Energía mecánica

Energía eléctrica



VENTAJAS Y DESVENTAJAS DE LA ENERGÍA TERMOSOLAR

Almacenamiento térmico:

- Baterías
- Materiales no escasos y no contaminantes

Hibridación:

- Combustión fósil o biomasa

Espejos no contaminantes:

- Paneles fotovoltaicos

Operación flexible:

- Potencia constante
- Períodos con nubes o noche
- Curva demanda
- Integración otras energías renovables

Pocas plantas a nivel comercial

Electricidad generada más cara que convencional

+ I+D:
+ Eficiencia
- Costes

ELEMENTOS COMUNES

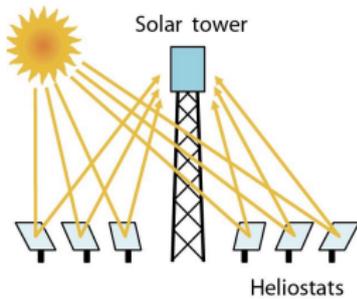


Tecnología de
concentración
(CSP):
Elementos
comunes

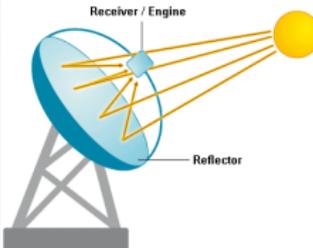


TIPOS DE CONCENTRADORES

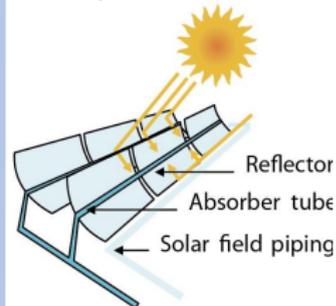
Torre central



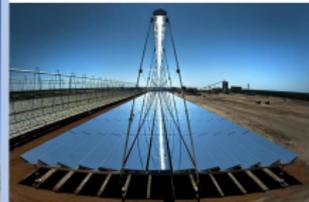
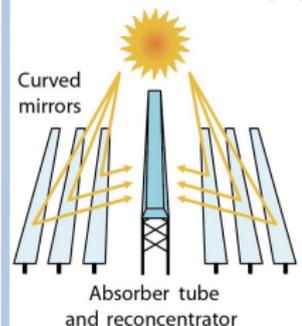
Discos parabólicos



Semicilindros parabólicos



Lineal de Fresnel





FACTOR DE CONCENTRACIÓN Y TEMPERATURA DEL COLECTOR

Solar energy collectors

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)
Stationary	Flat plate collector (FPC)	Flat	1	30–80
	Evacuated tube collector (ETC)	Flat	1	50–200
	Compound parabolic collector (CPC)	Tubular	1–5	60–240
Single-axis tracking			5–15	60–300
	Linear Fresnel reflector (LFR)	Tubular	10–40	60–250
	Parabolic trough collector (PTC)	Tubular	15–45	60–300
	Cylindrical trough collector (CTC)	Tubular	10–50	60–300
Two-axes tracking	Parabolic dish reflector (PDR)	Point	100–1000	100–500
	Heliostat field collector (HFC)	Point	100–1500	150–2000

Note: Concentration ratio is defined as the aperture area divided by the receiver/absorber area of the collector.



COMPARACIÓN DE TECNOLOGÍAS

	Parabolic troughs	Central receiver	Dish/engine
Power unit	30–80 MW ^a	10–200 MW ^a	5–25 kW
Temperature operation	390 °C	565 °C	750 °C
Annual capacity factor	23–50% ^a	20–77% ^a	25%
Peak efficiency	20%	23%	29.4%
Net annual efficiency	11–16% ^a	7–20% ^a	12–25%
Commercial status	Mature	Early projects	Prototypes-demos
Technology risk	Low	Medium	High
Thermal storage	Limited	Yes	Batteries
Hybrid schemes	Yes	Yes	Yes
<i>Cost W installed</i>			
\$ per W	3.49–2.34 ^a	3.83–2.16 ^a	11.00–1.14 ^a
\$ per Wpeak ^b	3.49–1.13 ^a	2.09–0.78 ^a	11.00–0.96 ^a

^a Data interval for the period 2010–2025. ^b Without thermal storage.

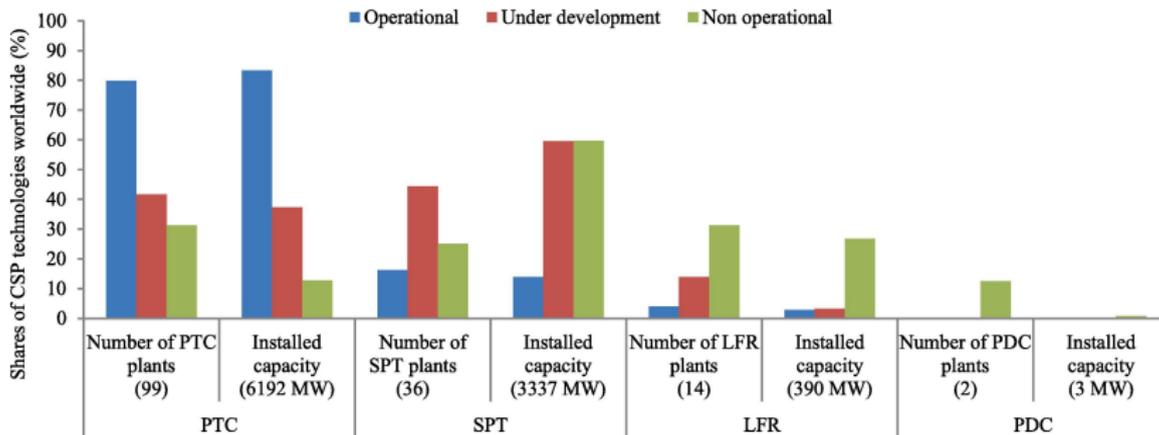
Annual capacity factor:

real energy produced during a year / eventual energy produced in the same period at full load



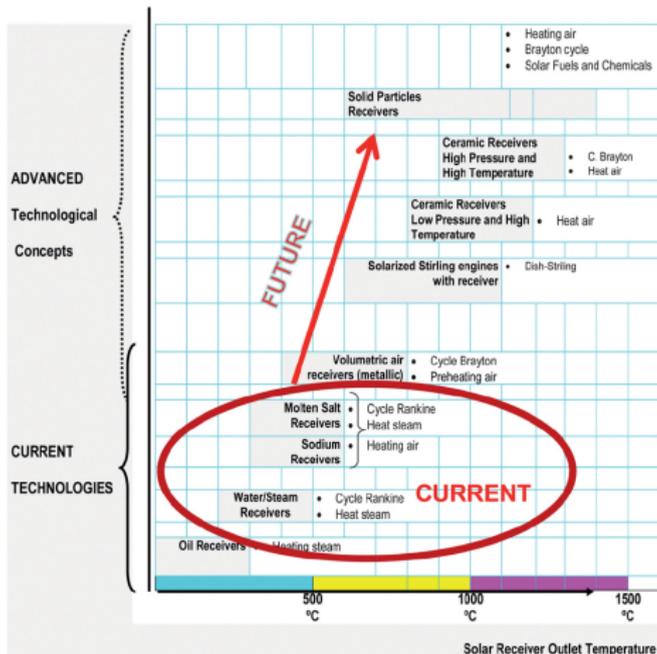
COMPARACIÓN DE TECNOLOGÍAS

Shares of worldwide CSP plants by technology (2020)



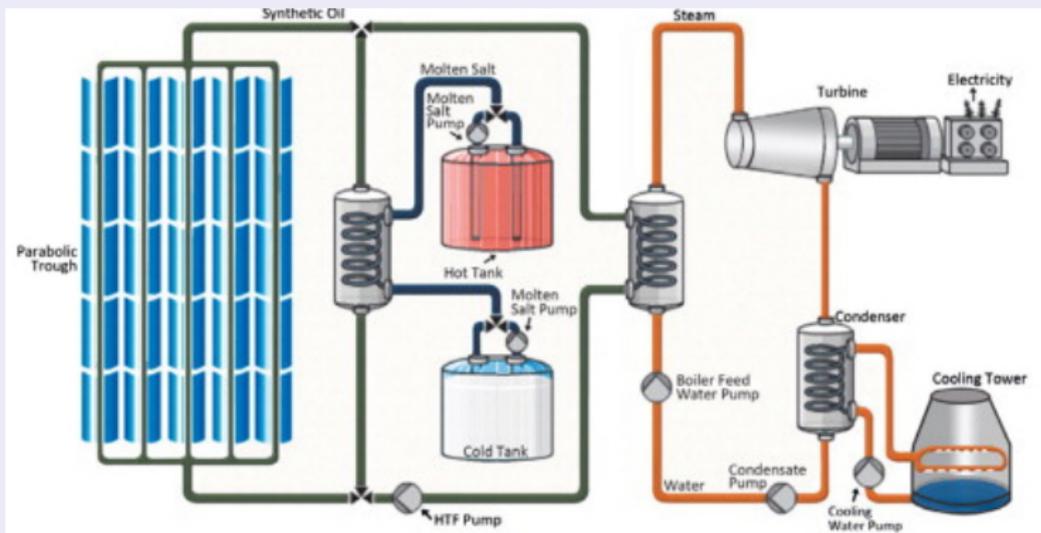
Note: number of plants and their installed capacity are detailed in accumulated terms
Achkari and El Fadar (2020)

PREVISIÓN DE EVOLUCIÓN FUTURA



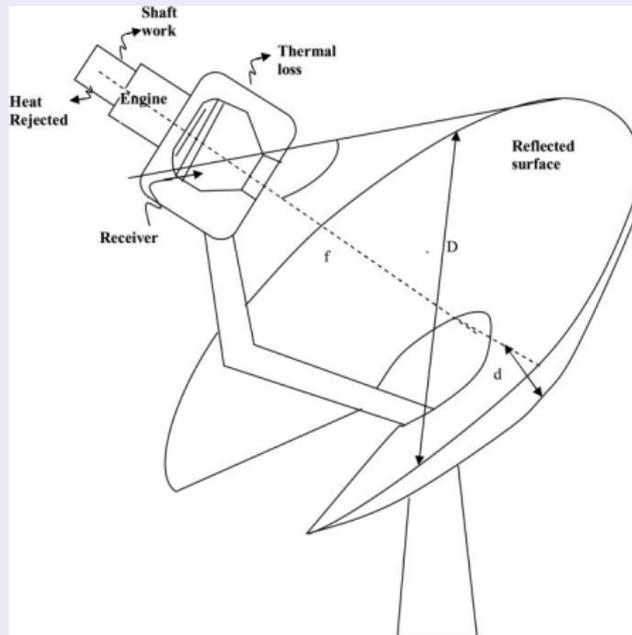
ESQUEMAS DE PLANTA

PLANTA DE TIPO *parabolic trough* CON ALMACENAMIENTO TÉRMICO (RANKINE)



ESQUEMAS DE PLANTA

PLANTA DE DISCO PARABÓLICO (BRAYTON O STIRLING)





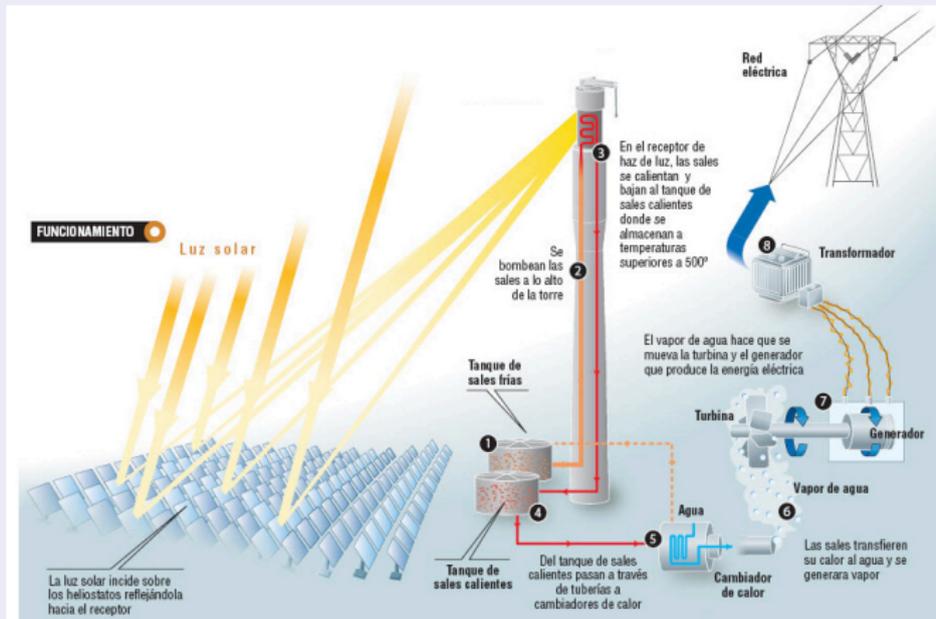
ESQUEMAS DE PLANTA

PLANTA DE DISCO PARABÓLICO (BRAYTON O STIRLING)



ESQUEMAS DE PLANTA

PLANTA DE TORRE CENTRAL CON ALMACENAMIENTO (RANKINE)





ESQUEMA

- 1 INTRODUCCIÓN. TIPOS DE CONCENTRADORES
- 2 PLANTA TERMOSOLAR PURA. MODELO TERMODINÁMICO
 - Eficiencia del subsistema solar
 - Eficiencia del ciclo termodinámico
 - Eficiencia global. Optimización respecto a τ
 - Doble optimización
- 3 PLANTAS HÍBRIDAS TIPO BRAYTON



SISTEMA SOLAR PURO. EFICIENCIA GLOBAL DE LA PLANTA

EFICIENCIA TÉRMICA GLOBAL DE LA PLANTA, η

$$\eta = \frac{|\dot{W}|}{GA_a} = \frac{|\dot{W}|}{|\dot{Q}_H|} \frac{|\dot{Q}_H|}{GA_a} \equiv \eta_h \eta_s$$

η_h : eficiencia del ciclo termodinámico (Brayton, Rankine...)

η_s : eficiencia del colector solar

G : irradiancia solar directa (W/m^2)

A_a : área de apertura



EFICIENCIA TÉRMICA DEL RECEPTOR SOLAR

CALOR POR UNIDAD DE TIEMPO CEDIDO POR EL RECEPTOR

Planta termosolar con campo de heliostatos y torre central:

$$|\dot{Q}_H| = \eta_0 G A_a - U_L A_r T_L (\tau - 1)$$

Eficiencia del subsistema solar:

$$\eta_s = \frac{|\dot{Q}_H|}{G A_a} = \eta_0 [1 - (\tau - 1) M]$$

η_0 : eficiencia óptica

A_a : área de apertura (factor de concentración: $C = A_a/A_r$)

$\tau = T_H/T_L$: relación entre las temperaturas de las fuentes

U_L : coeficiente efectivo de pérdidas

$$M \equiv U_L T_L / (\eta_0 G C)$$



EJEMPLO: PLANTA GEMASOLAR





EJEMPLO: PLANTA GEMASOLAR

Status Date: March 20, 2017

Background

Technology: Power tower
Status: Operational
Country: Spain
City: Fuentes de Andalucía
Region: Andalucía (Sevilla)
Lat/Long Location: 37°33' 44.95" North, 5°19' 49.39" West
Land Area: 195 hectares
Solar Resource: 2,100 kWh/m²/yr
Source of Solar Resource: Sener
Electricity Generation: 80,000 MWh/yr
Contact(s): Juan Ignacio Burgaleta
Company: Sener
Break Ground: February 2009
Start Production: April 2011
Cost (approx): 230,000,000 Euro
Construction Job-Years: 800
Annual O&M Jobs: 45

Participants

Developer(s): Torresol Energy
Owner(s) (%): MASDAR (40%)
Sener (60%)
EPC Contractor: UTE C.T. Solar Tres
Operator(s): Torresol O&M

Plant Configuration

Solar Field

Heliostat Solar-Field
Aperture Area: 304,750 m²
of Heliostats: 2,650
Heliostat Aperture Area: 120.0 m²
Heliostat Manufacturer: Sener
Heliostat Description: Sheet metal stamped facet
Heliostat Drive
Manufacturer: Sener
Tower Height: 140 m
Receiver Manufacturer: Sener
Heat-Transfer Fluid
Type: Molten salts (sodium and potassium nitrates)
Receiver Inlet Temp: 290C
Receiver Outlet Temp: 565C
Receiver Temp.
Difference: 275C

Power Block

Turbine Capacity (Gross): 19.9 MW
Turbine Capacity (Net): 19.9 MW
Output Type: Steam Rankine
Cooling Method: Wet cooling

Thermal Storage

Storage Type: 2-tank direct
Storage Capacity: 15 hour(s)
Thermal Storage
Description: One cold-salts tank (290°C) from where salts are pumped to the tower receiver and heated up to 565°C, to be stored in one hot-salts tank (565°C).
Annual equivalent hours = 5,000.

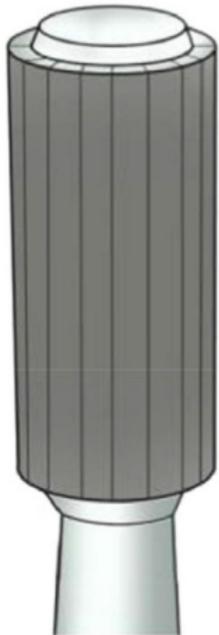
<https://www.nrel.gov/csp/solarpaces/>



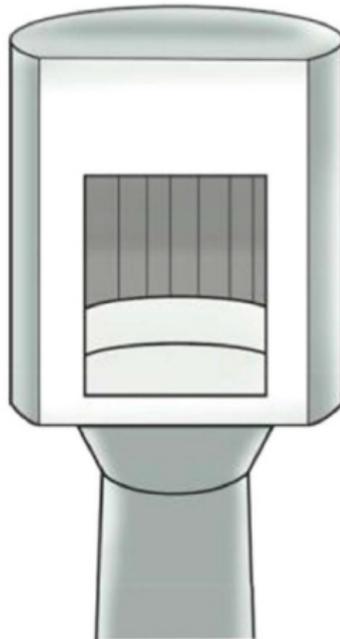
EJEMPLO: PLANTA GEMASOLAR



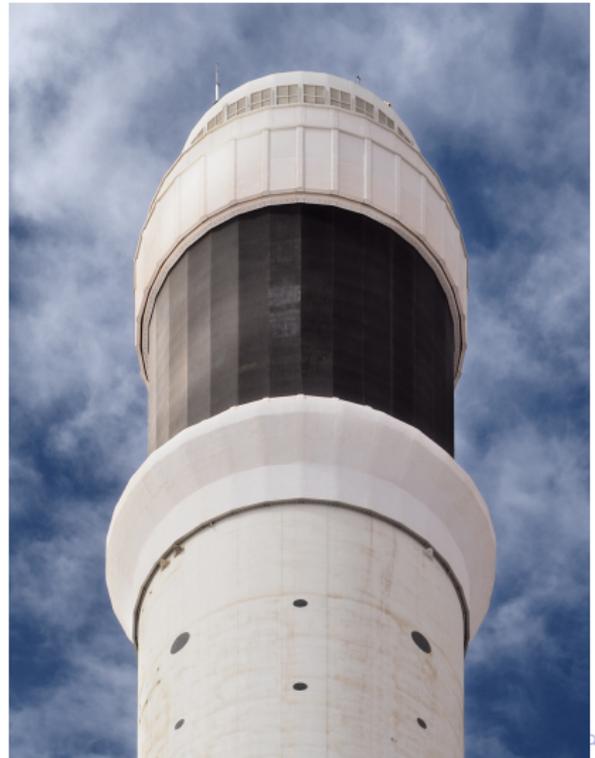
RECEPTORES TUBULARES Y DE CAVIDAD



Tubular receiver



Cavity receiver



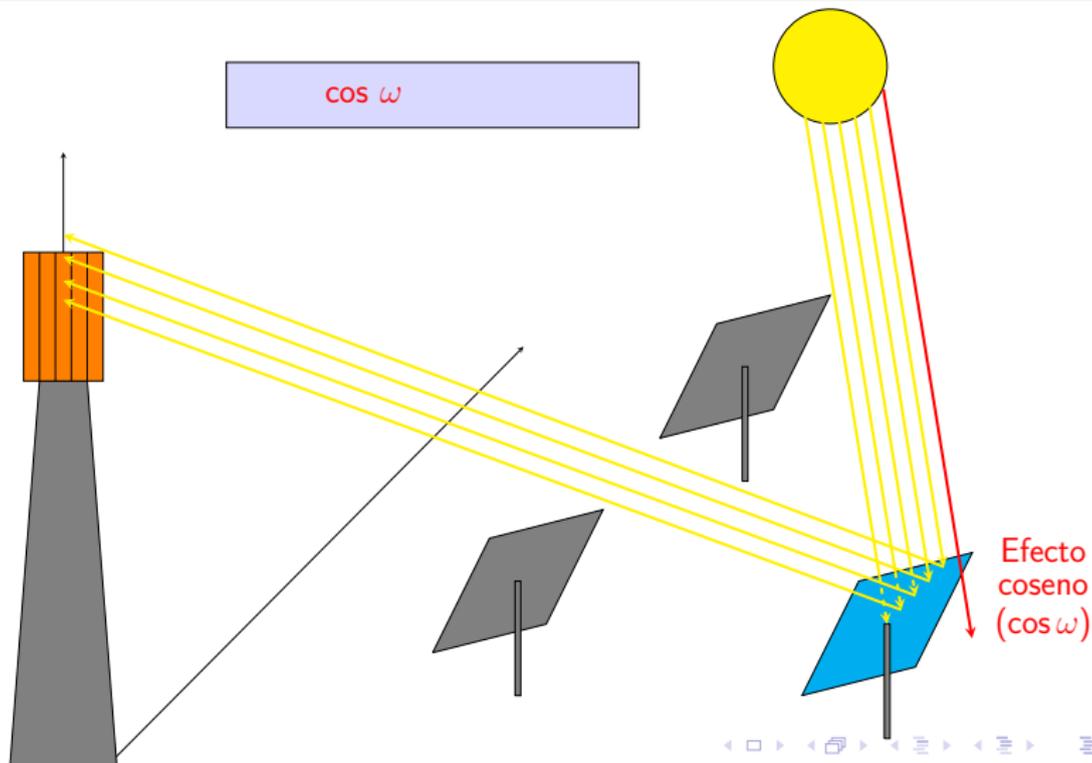


EFICIENCIA ÓPTICA

$$\eta_o = \cos \omega \cdot f_b \cdot f_{sh} \cdot f_{sp} \cdot f_{at} \cdot \rho$$

- $\cos \omega$, coseno incidente de la radiación solar.
- f_b y f_{sh} , factor de bloqueo y sombras.
Depende del tamaño de los heliostatos y la distancia entre ellos.
- f_{sp} , factor de *spillage* o desbordamiento.
Depende de la precisión del sistema de seguimiento de los heliostatos. Se disminuye aumentando el tamaño del receptor, pero mayor tamaño significa también mayores pérdidas térmicas.
- f_{at} , factor de atenuación atmosférica.
Se representa mediante una función polinómica de la distancia de los heliostatos al receptor central.
- ρ , reflectividad de los espejos.

EFFECTO COSENO



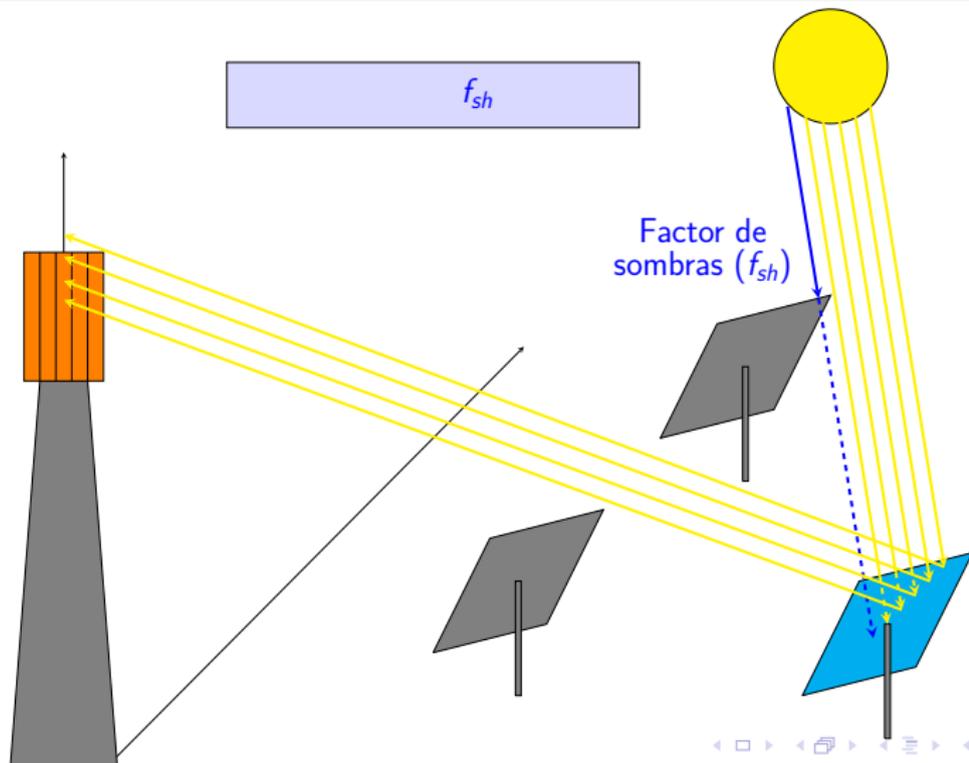
Tipos de concentradores
Modelo de planta termosolar
Plantas híbridas tipo Brayton

Eficiencia del subsistema solar
Eficiencia del ciclo termodinámico
Eficiencia global. Optimización respecto a τ
Doble optimización





FACTOR DE SOMBRAS

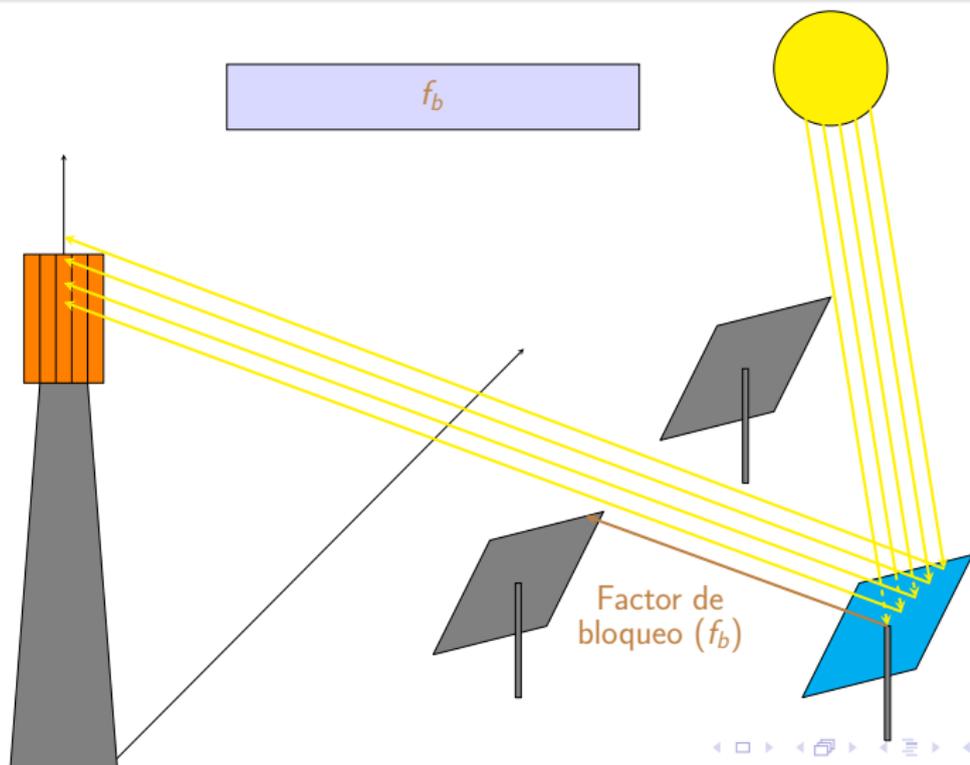


Tipos de concentradores
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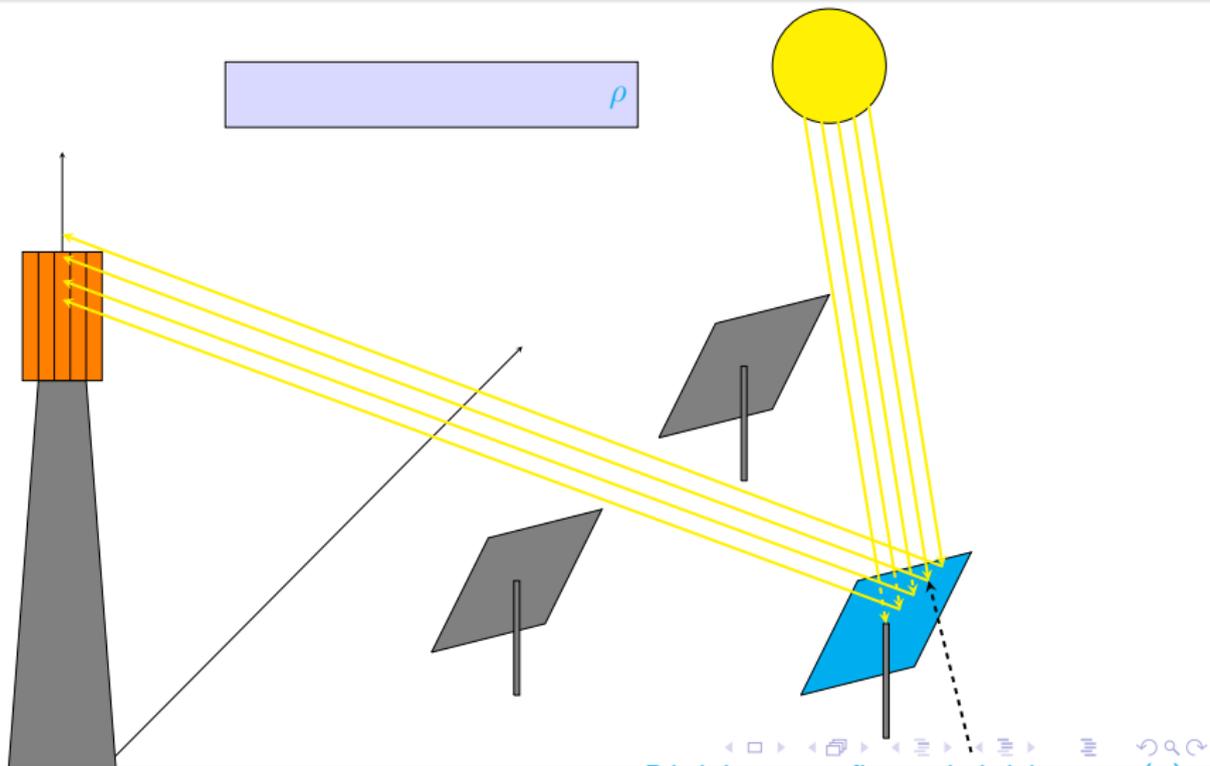


FACTOR DE BLOQUEO





REFLECTIVIDAD DEL ESPEJO

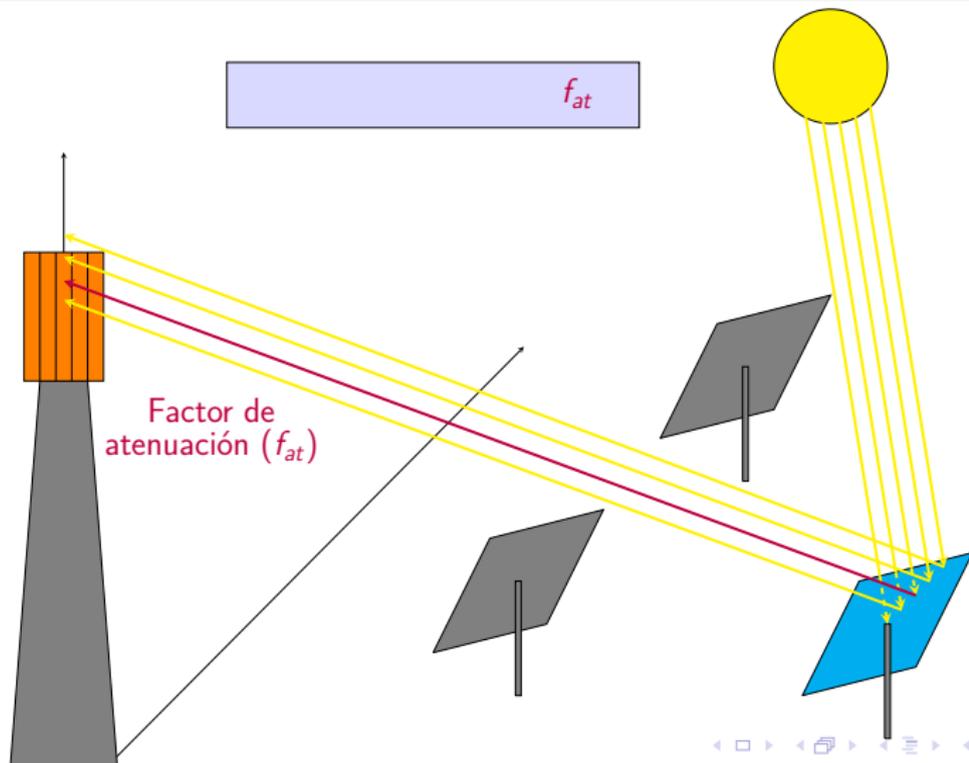


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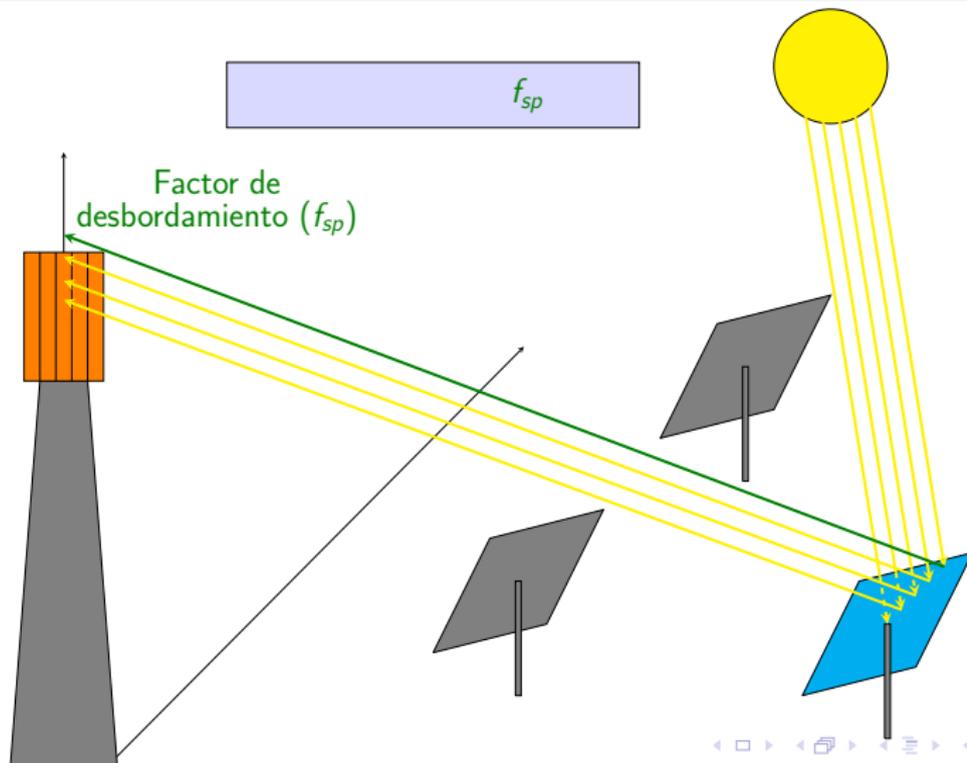


FACTOR DE ATENUACIÓN



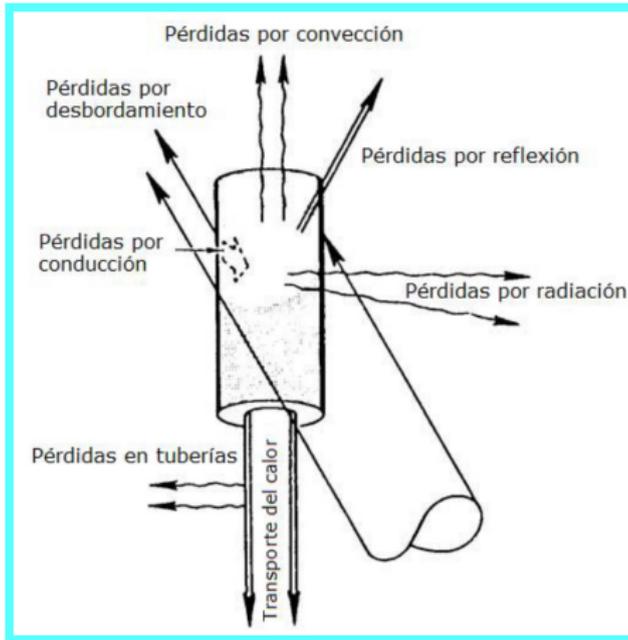


FACTOR DE DESBORDAMIENTO (*spillage*)



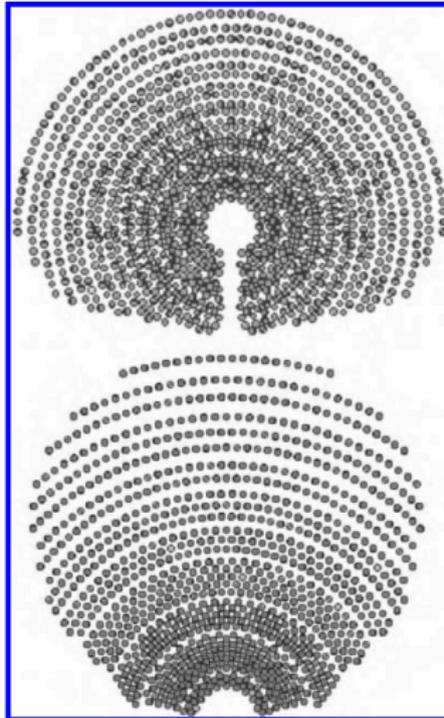


PÉRDIDAS TÉRMICAS EN EL RECEPTOR





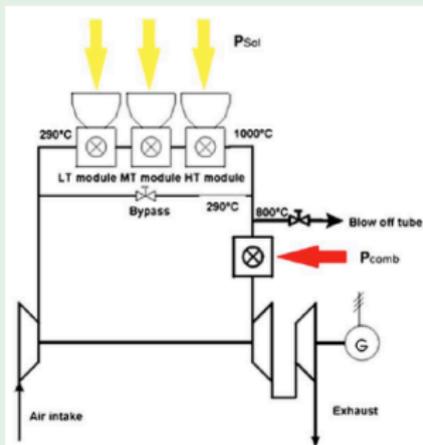
OPTIMIZACIÓN DEL CAMPO DE HELIOSTATOS



EJEMPLO DE UN PROYECTO TIPO BRAYTON

SOLGATE PROJECT

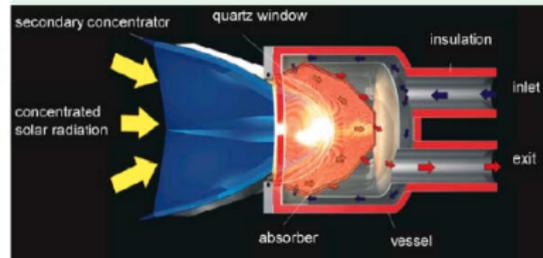
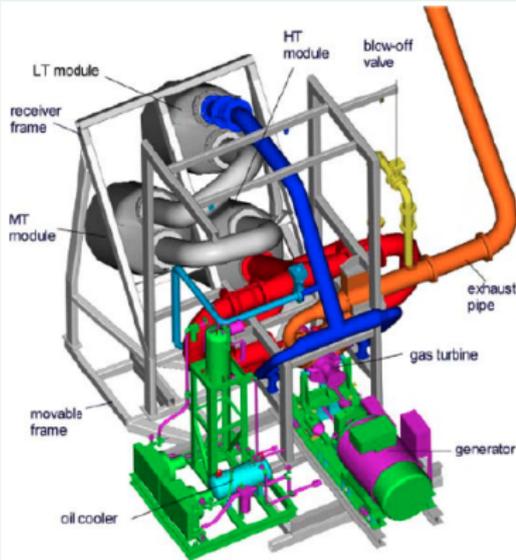
(EC PROJECT, 2006), PLATAFORMA SOLAR DE ALMERÍA (SPAIN)



Thermal Power: 1 MW
Heliostat field: CESA-1
Three modules: 290°C to 1000°C
Combustion chamber: kerosen
Thermal efficiency: $\sim 20\%$

P. Heller *et al.*, Sol. Energy, 80, 1225-1230
(2006)

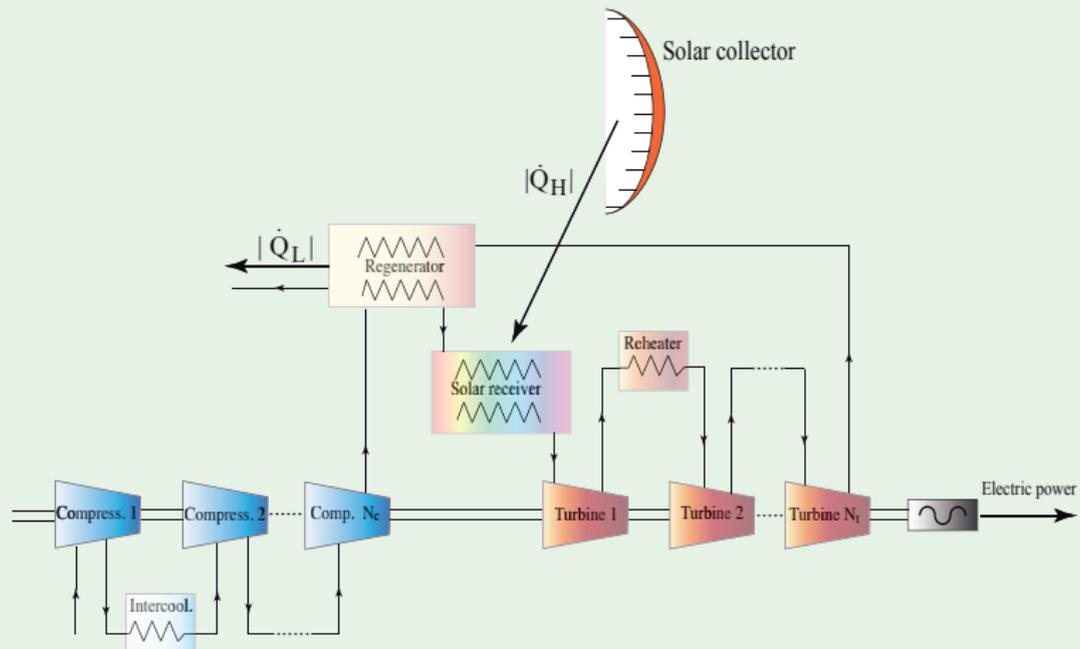
SOLGATE PROJECT



Volumetric receiver

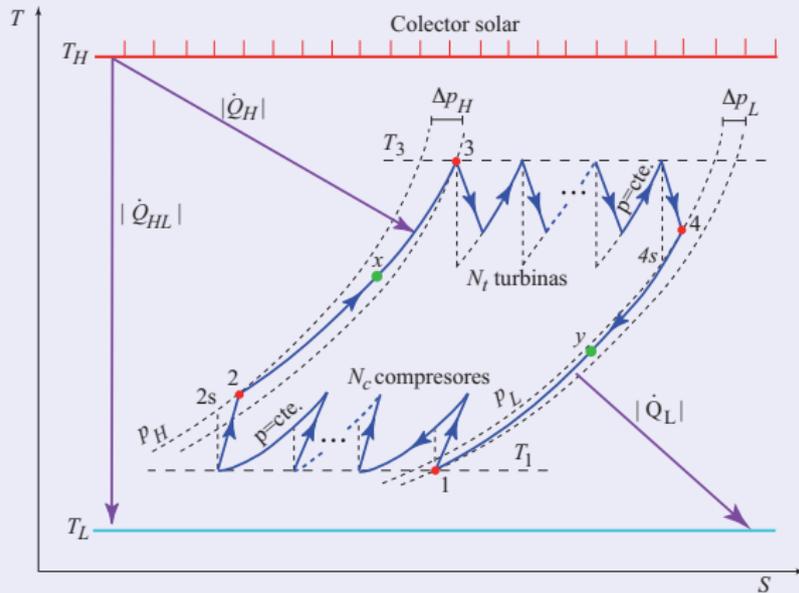
PLANTA TERMOSOLAR PURA TIPO BRAYTON MULTITETAPA

ESQUEMA DE COMPONENTES



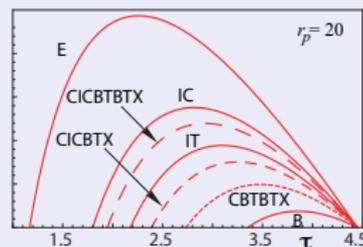
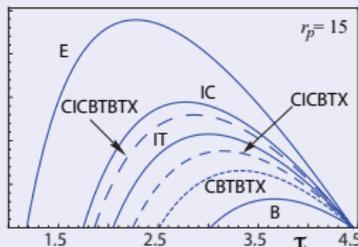
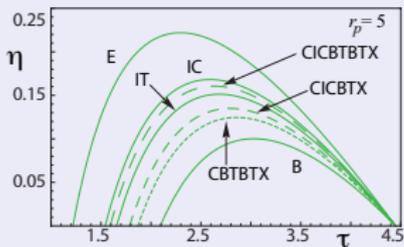
PLANTA TERMOSOLAR PURA TIPO BRAYTON MULTITETAPA

DIAGRAMA $T - S$





RENDIMIENTO GLOBAL DE LA PLANTA



Parámetros del colector solar: $\eta_0 = 0,84$, $M = 0,29$

Parámetros del ciclo Brayton:

$\epsilon_H = \epsilon_L = 0,90$, $\gamma = 1,4$, $\rho_H = \rho_L = 0,98$, $\epsilon_t = \epsilon_c = 0,95$, $\epsilon_r = 0,95$, $\xi = 0,02$



OPTIMIZACIÓN SIMULTÁNEA RESPECTO A τ Y r_p

INFLUENCIA DE $\epsilon_L = \epsilon_H \equiv \epsilon$

ϵ	$\eta_{\max, \max}$			$r_{p, \max}$			$\tau_{\max, \max}$		
	0,75	0,90	1	0,75	0,90	1	0,75	0,90	1
CBTX	0.103	0.127	0.141	2.155	2.455	2.700	2.877	2.755	2.691
CBTBTX	0.117	0.141	0.155	2.347	2.753	3.105	2.798	2.686	2.628
CICBTX	0.126	0.146	0.158	2.529	2.898	3.191	2.752	2.660	2.612
CICBTBTX	0.144	0.164	0.175	2.985	3.573	4.071	2.659	2.581	2.539

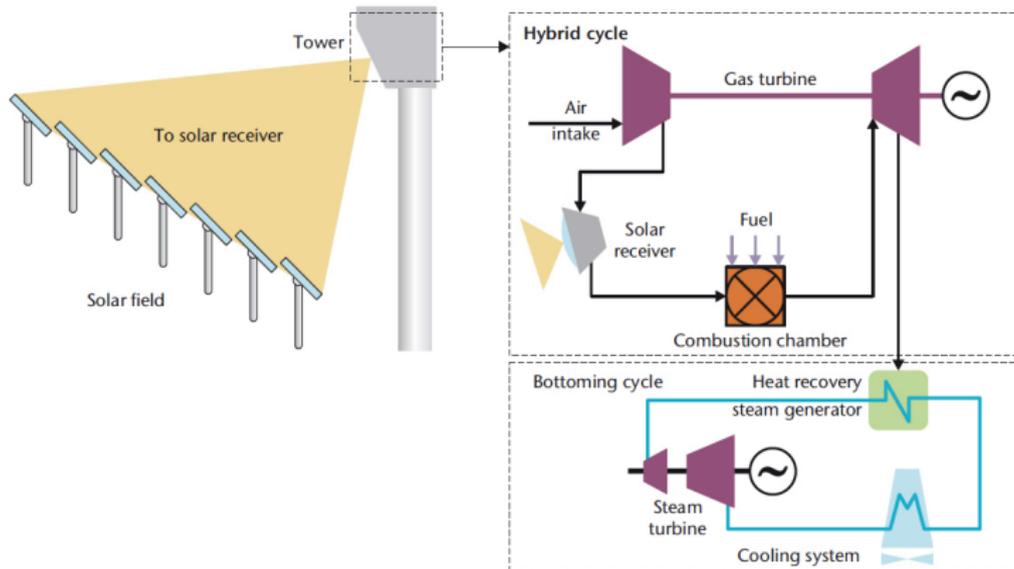
Temperaturas óptimas en el intervalo ($T_L = 300$ K): 762 – 863 K



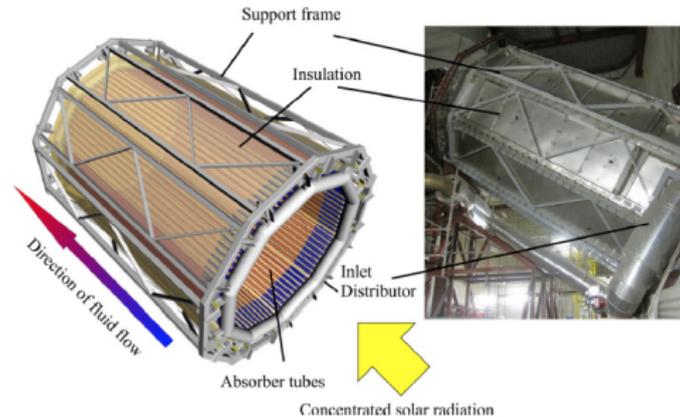
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- 2 PLANTA TERMOSOLAR PURA. MODELO TERMODINÁMICO
- 3 PLANTAS HÍBRIDAS TIPO BRAYTON
 - Proyecto SOLUGAS
 - Simulación termodinámica
 - Validación del modelo
 - Resultados numéricos: estacionales y diarios
 - Análisis termo-económico

ESQUEMA DE UNA PLANTA HÍBRIDA DE TIPO COMBINADO

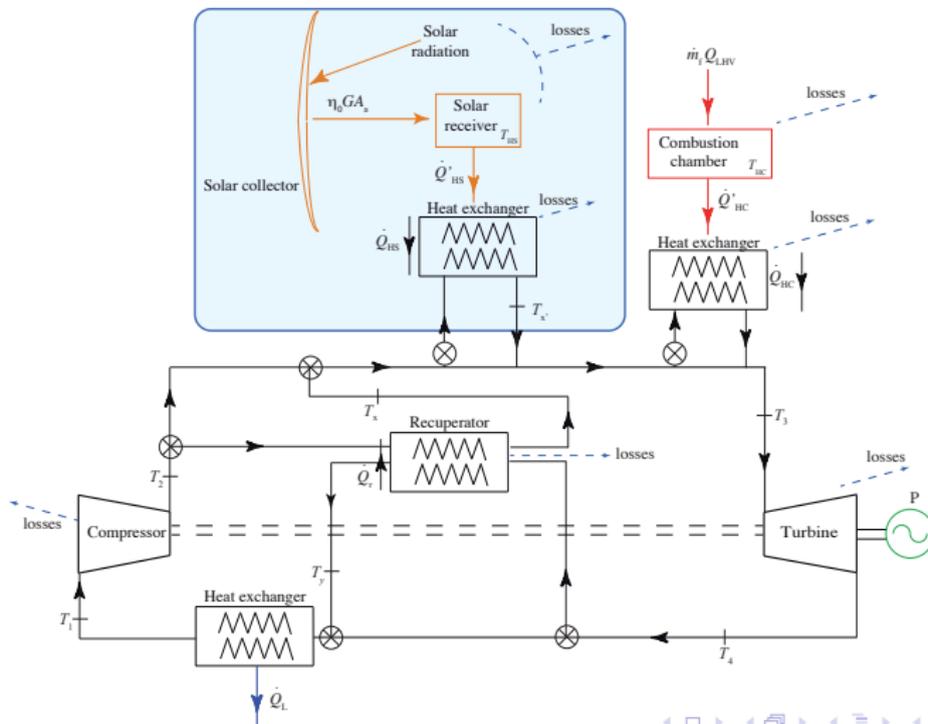


RECEPTOR DE SOLUGAS



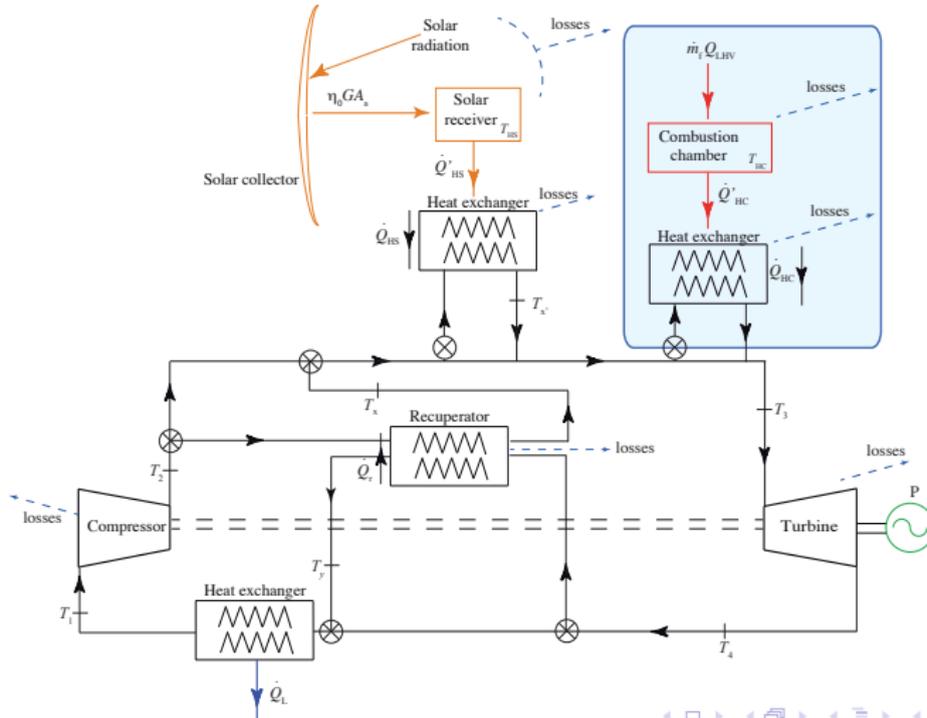


SIMULACIÓN TERMODINÁMICA. SUBSISTEMAS: COLECTOR SOLAR



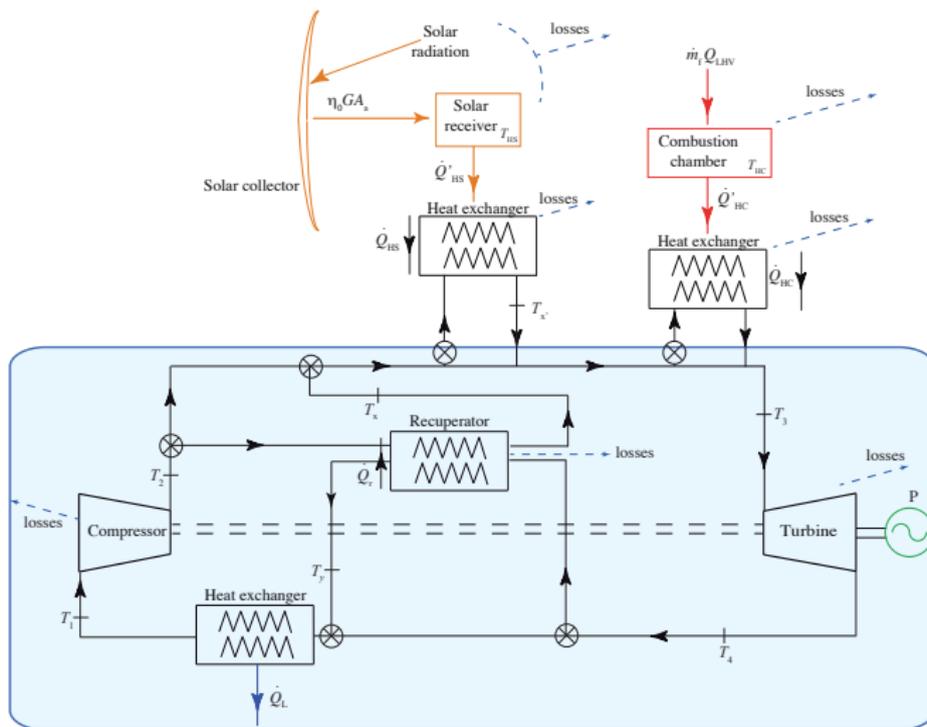


SIMULACIÓN TERMODINÁMICA. SUBSISTEMAS: CÁMARA DE COMBUSTIÓN

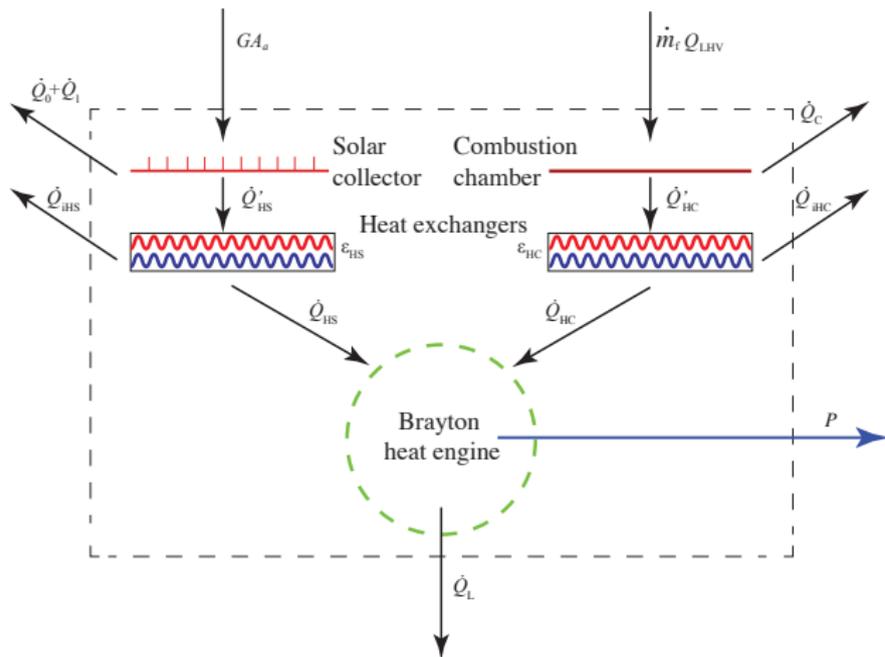




SIMULACIÓN TERMODINÁMICA. SUBSISTEMAS: CICLO BRAYTON



TRANSFERENCIAS DE CALOR



CALORES TRANSFERIDOS

$$|\dot{Q}_{HS}| = \dot{m} \int_{T_x}^{T_{x'}} c_w(T) dT$$

$$|\dot{Q}_{HC}| = \dot{m} \int_{T_{x'}}^{T_3} c_w(T) dT$$

$$|\dot{Q}_H| = |\dot{Q}_{HS}| + |\dot{Q}_{HC}|$$

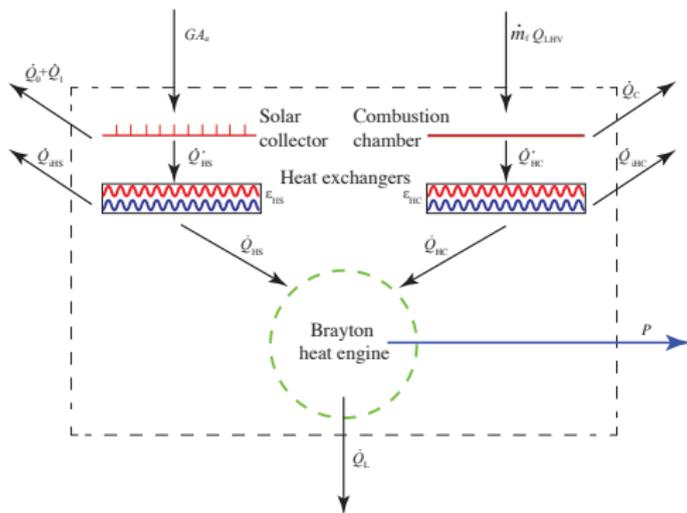
$$|\dot{Q}_L| = \dot{m} \int_{T_y}^{T_1} c_w(T) dT$$

$$P = |\dot{Q}_H| - |\dot{Q}_L|$$

Solar share

$$f = \frac{|\dot{Q}_{HS}|}{|\dot{Q}_{HS}| + |\dot{Q}_{HC}|}$$

TRANSFERENCIAS DE CALOR



EFICIENCIA TÉRMICA GLOBAL

$$\eta = \eta_h \eta_s \eta_c \left[\frac{\epsilon_{HS} \epsilon_{HC}}{\eta_c f \epsilon_{HC} + \eta_s (1 - f) \epsilon_{HS}} \right]$$

EFICIENCIAS DE LOS SUBSISTEMAS

$$\eta = \frac{|\dot{W}|}{|\dot{Q}_{abs}|} = \frac{P}{G A_a + \dot{m}_f Q_{LHV}}$$

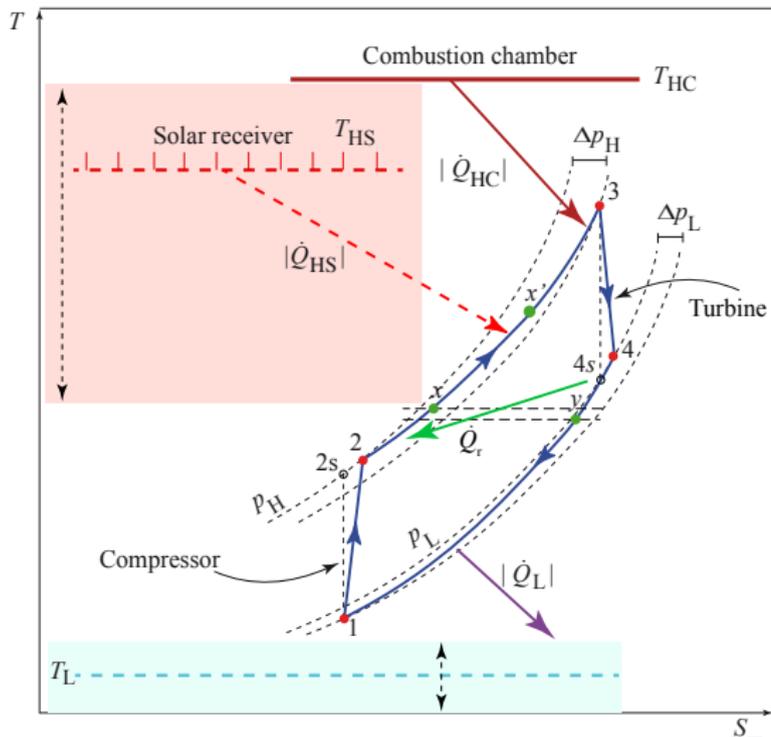
$$\eta_s = \frac{|\dot{Q}'_{HS}|}{G A_a} = \frac{|\dot{Q}_{HS}| / \epsilon_{HS}}{G A_a}$$

$$\eta_c = \frac{|\dot{Q}'_{HC}|}{\dot{m}_f Q_{LHV}} = \frac{|\dot{Q}_{HC}| / \epsilon_{HC}}{\dot{m}_f Q_{LHV}}$$

$$\eta_h = \frac{|\dot{W}|}{|\dot{Q}_H|} = \frac{P}{|\dot{Q}_{HS}| + |\dot{Q}_{HC}|}$$

$$\eta_e = \frac{P}{\dot{m}_f Q_{LHV}}$$

DIAGRAMA $T - S$



PARÁMETROS

T_{HS}

T_{HC}

r_p

ϵ_c

ϵ_r

ϵ_{HS}

ϵ_{HC}

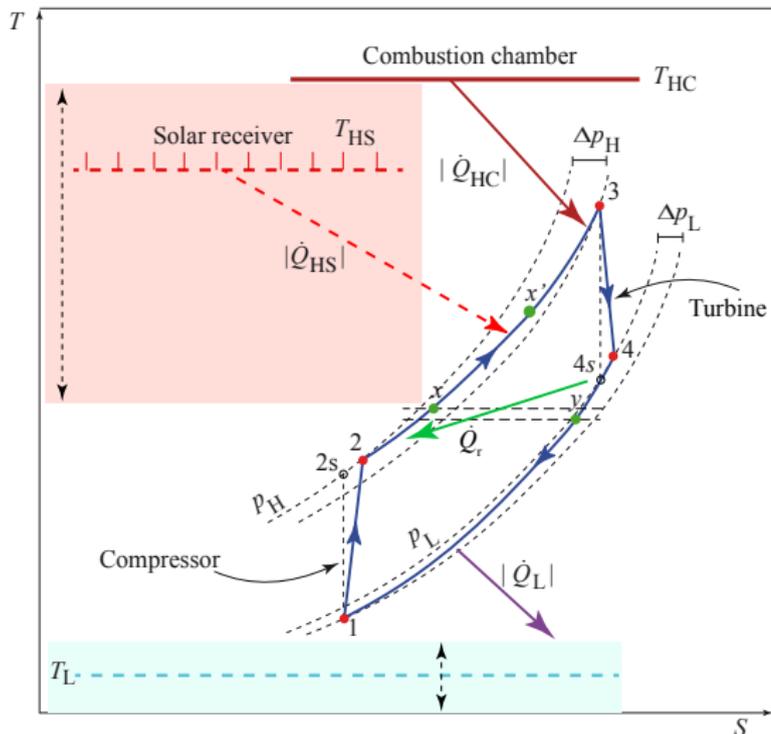
ϵ_t

ϵ_L

ρ_H

ρ_L

DIAGRAMA $T - S$



PARÁMETROS

T_{HS}

T_{HC}

r_p

ϵ_c

ϵ_r

ϵ_{HS}

ϵ_{HC}

ϵ_t

ϵ_L

ρ_H

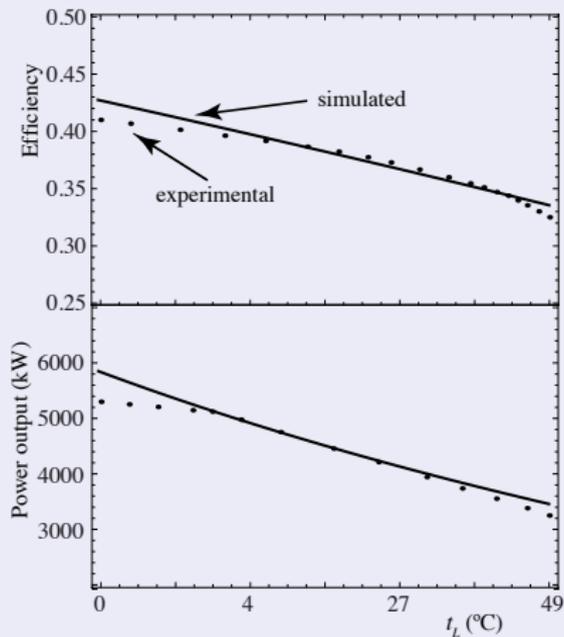
ρ_L

VALIDACIÓN DE RESULTADOS PARA LA TURBINA (*Mercury 50, Caterpillar*)

<i>Mercury 50</i> manufacturer's specifications			
$\dot{m} = 17,9 \text{ kg/s}$	$r_p = 9,9$	$T_L = 288 \text{ K}$	
Measured output parameters			
$T_3 = 1423 \text{ K}$	$T_y = 647 \text{ K}$	$\eta = 0,385$	$P = 4,6 \text{ MW}$
Assumed losses parameters			
$\epsilon_{HC} = 0,98$	$\rho_H = \rho_L = 0,97$	$\epsilon_t = 0,885$	$\epsilon_r = 0,775$
$\epsilon_L = 1$		$\epsilon_c = 0,815$	
Calculated values			
$T_3 = 1418 \text{ K}$	$T_y = 650 \text{ K}$	$\eta_H = 0,387$	$P = 4,5 \text{ MW}$
Relative deviations			
T_3	T_y	η_H	P
0.4%	0.4%	0.6%	1.4%

VALIDACIÓN DE LA TURBINA (*Mercury 50, Caterpillar*)

EVOLUCIÓN DE RENDIMIENTO CON LA TEMPERATURA AMBIENTE, t_L



PARÁMETROS DE TRABAJO Y VALIDACIÓN (PROYECTO SOLUGAS)

Solar plant parameters at design point

$$\eta_0 = 0,65$$

$$\alpha = 0,1$$

$$T_{HS} = 1088 \text{ K}$$

$$\sigma = 5,67 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \text{K}^4}$$

$$\epsilon_{HS} = 0,78$$

$$C = 425,2$$

$$G = 860 \text{ W/m}^2$$

$$\bar{U}_L = 5 \frac{\text{W}}{\text{m}^2 \text{K}}$$

Estimated output parameters

$$T_3 = 1422 \text{ K}$$

$$f = 0,341$$

$$\dot{m}_f = 0,172 \text{ kg/s}$$

$$|\dot{W}| = 4,2 \text{ MW}$$

Estimated efficiencies

$$\eta_h = 0,393$$

$$\eta_s = 0,698$$

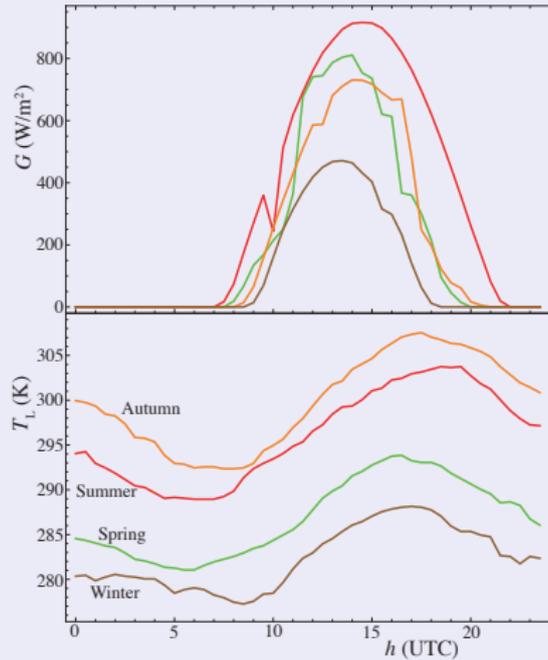
$$\eta = 0,300$$

$$\eta_e = 0,647$$



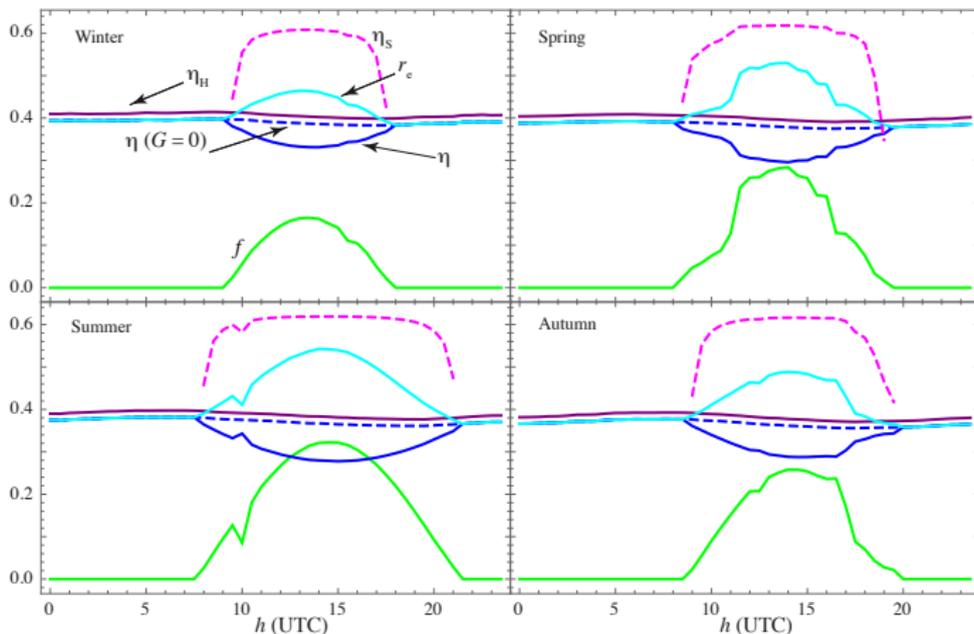
RESULTADOS NUMÉRICOS: ESTACIONALES Y DIARIOS

DATOS ESTACIONALES DE IRRADIANCIA Y TEMPERATURA AMBIENTE

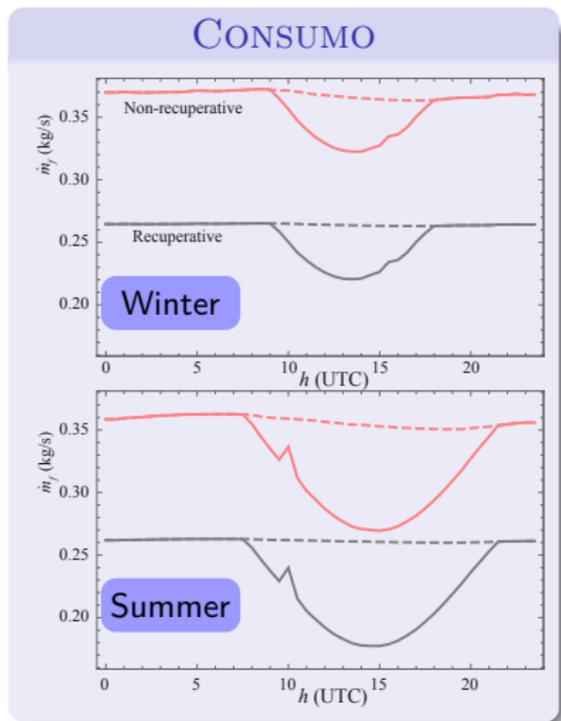




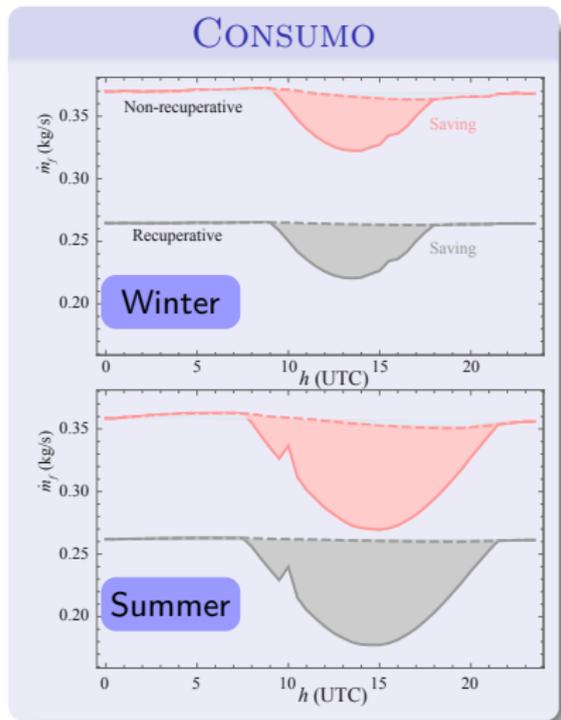
EVOLUCIÓN DIARIA/ESTACIONAL DE EFICIENCIAS (CON RECUPERACIÓN)



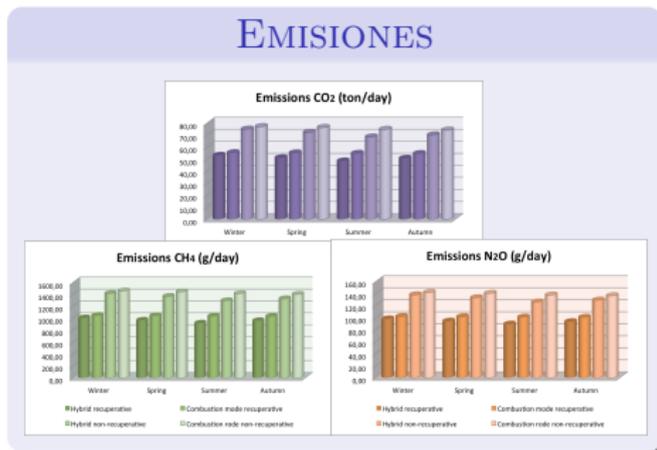
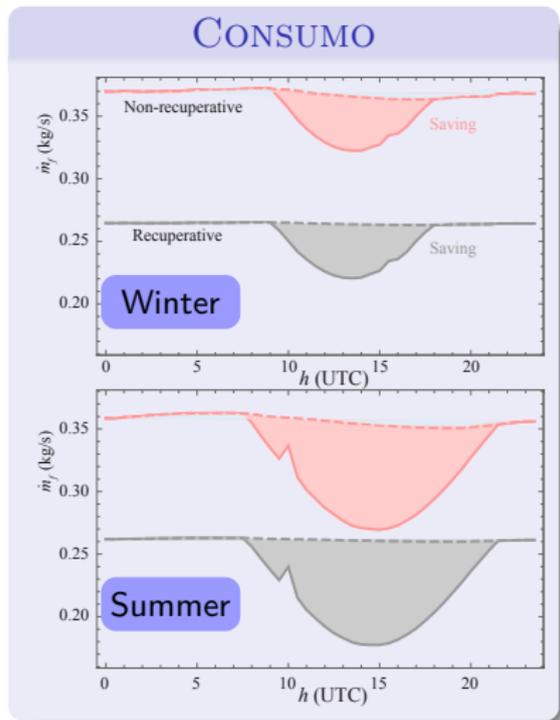
CONSUMO Y EMISIONES (CON Y SIN RECUPERACIÓN)



CONSUMO Y EMISIONES (CON Y SIN RECUPERACIÓN)

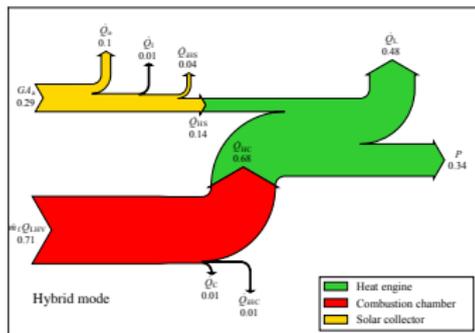


CONSUMO Y EMISIONES (CON Y SIN RECUPERACIÓN)

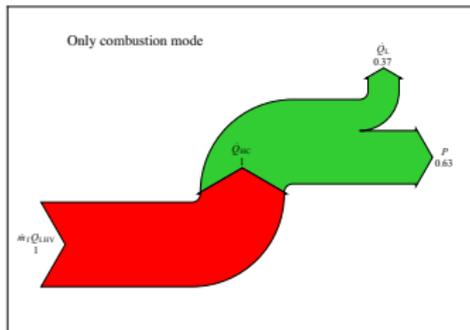
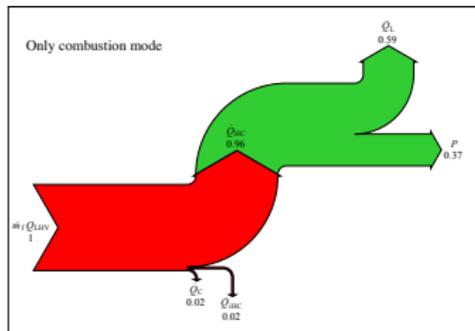
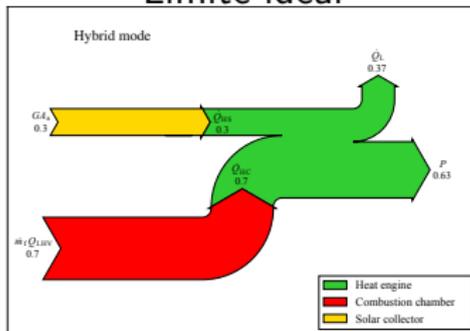


ANÁLISIS DE PÉRDIDAS. DIAGRAMAS DE SANKEY

Sistema real



Límite ideal





MAPA DE EFICIENCIA DEL CAMPO DE HELIOSTATOS

0.60 > Efficiency \geq 0.55 \Rightarrow 

0.55 > Efficiency \geq 0.50 \Rightarrow 

0.50 > Efficiency \geq 0.45 \Rightarrow 

0.45 > Efficiency \geq 0.40 \Rightarrow 

0.40 > Efficiency \geq 0.35 \Rightarrow 

0.35 > Efficiency \geq 0.30 \Rightarrow 

0.30 > Efficiency \geq 0.25 \Rightarrow 

0.25 > Efficiency \geq 0.20 \Rightarrow 

0.20 > Efficiency \geq 0.15 \Rightarrow 

0.15 > Efficiency \geq 0.10 \Rightarrow 

0.10 > Efficiency \geq 0.05 \Rightarrow 

0.05 > Efficiency \geq 0.00 \Rightarrow 



TERMO-ECONOMÍA

LCoE

LCoE (Levelized Cost of Electricity): Precio mínimo al que hay que vender la electricidad para que la planta sea rentable económicamente

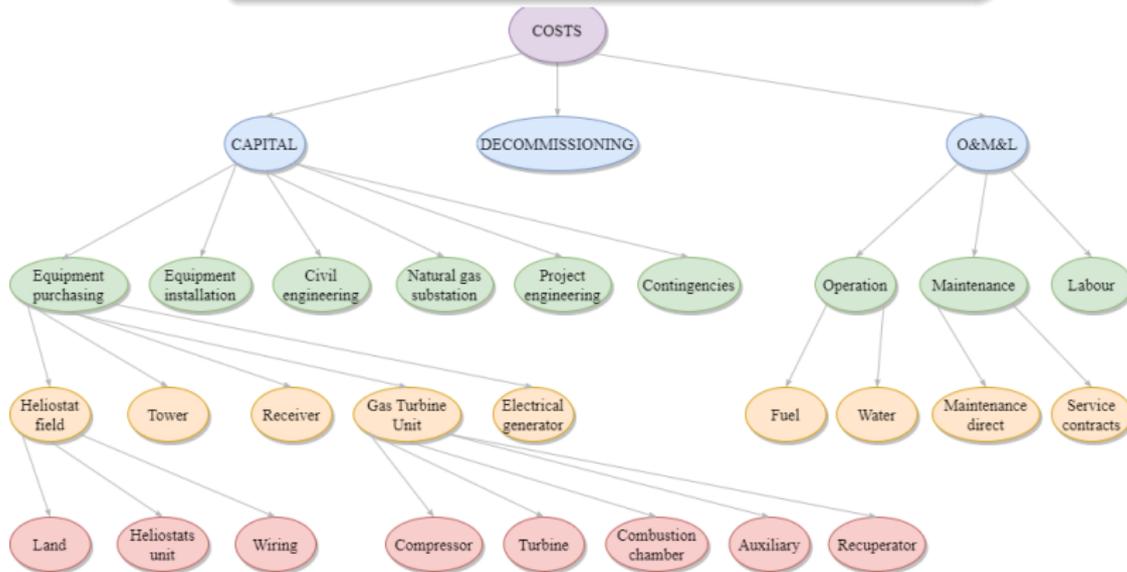
$$LCoE = \frac{\beta_{inv} C_{inv} + \beta_{dec} C_{dec} + C_{OML}}{E_{net}}$$

$$\beta_{inv} = \frac{(1+i)^{n_{con}} - 1}{i \cdot n_{con}} \frac{i(1+i)^{n_{op}}}{(1+i)^{n_{op}} - 1} + k_{ins}$$

$$\beta_{dec} = \frac{(1+i)^{n_{dec}} - 1}{i \cdot n_{dec} (1+i)^{n_{dec}-1}} \frac{i}{(1+i)^{n_{op}} - 1}$$

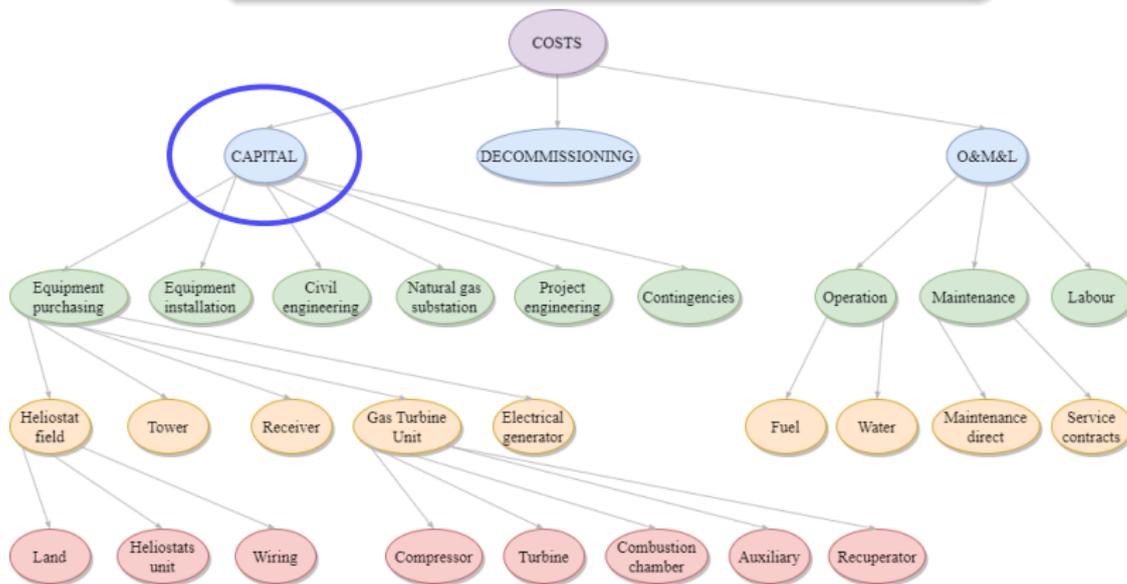
TERMO-ECONOMÍA

$$LCoE = \frac{\beta_{inv} C_{inv} + \beta_{dec} C_{dec} + C_{OML}}{E_{net}}$$



TERMO-ECONOMÍA

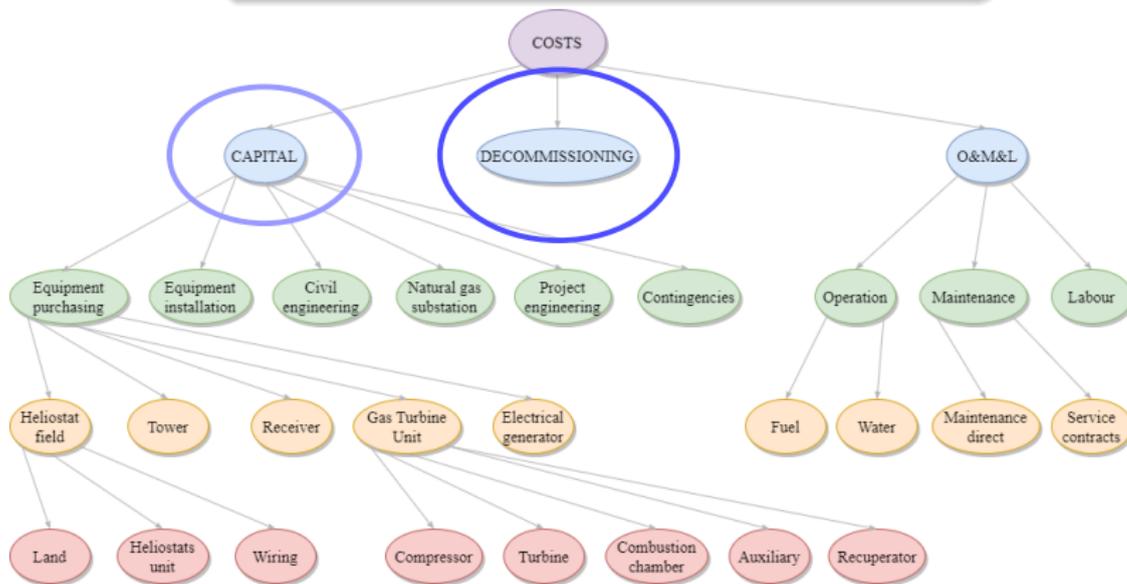
$$LCoE = \frac{\beta_{inv} C_{inv} + \beta_{dec} C_{dec} + C_{OML}}{E_{net}}$$





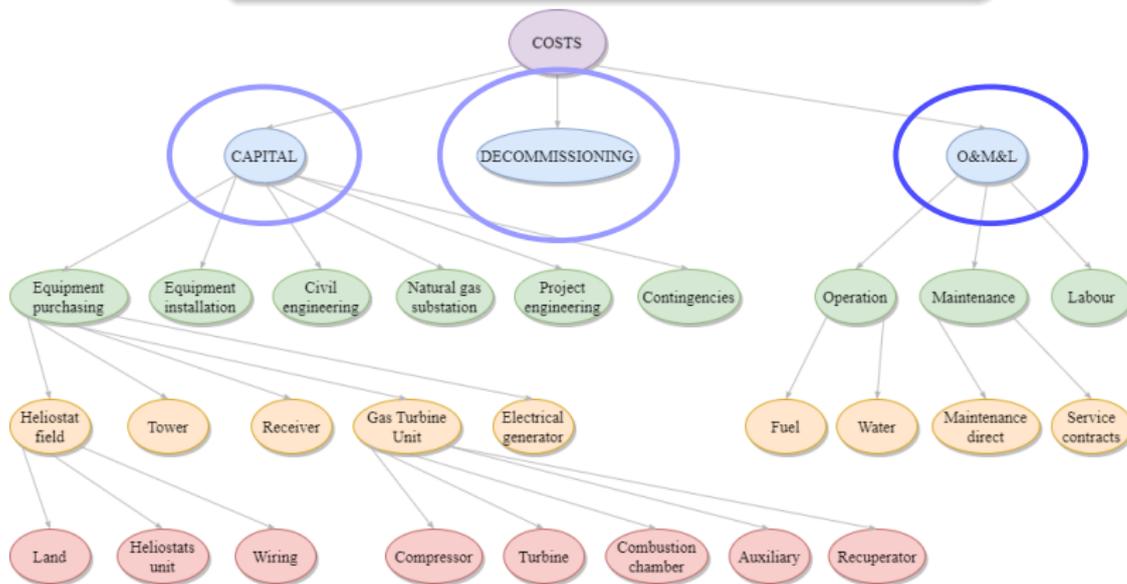
TERMO-ECONOMÍA

$$LCoE = \frac{\beta_{inv} C_{inv} + \beta_{dec} C_{dec} + C_{OML}}{E_{net}}$$



TERMO-ECONOMÍA

$$LCoE = \frac{\beta_{inv} C_{inv} + \beta_{dec} C_{dec} + C_{OML}}{E_{net}}$$





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