Concentrating Solar Power Technologies and Innovations

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Speeches 1 & 2 of 4:

1) Solar thermal Power Plants. On the verge to Commercialization

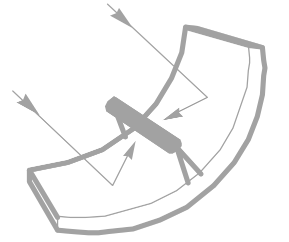
(To introduce the technology, the survey the context, the potential, the glabal and Mediterranean market, oportunities, ...)

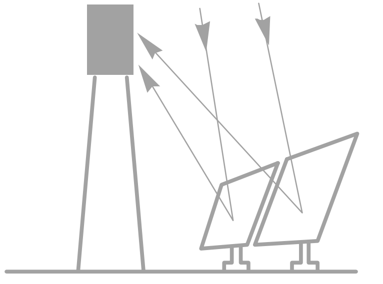
2) Concentrating Solar Power Technologies and Innovations

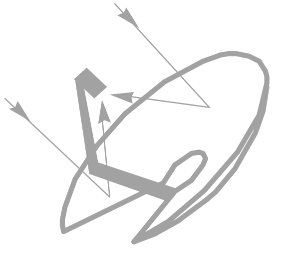
(To introduce the technological options, the status of the technologies, the roadmap for cost reduction and innovations, …)

Outline

- Component's basis
  - Concentrators
  - Receivers
  - "solarization" of cycles
- Power plants
  - Actual projects
  - Innovations







Why Concentration?

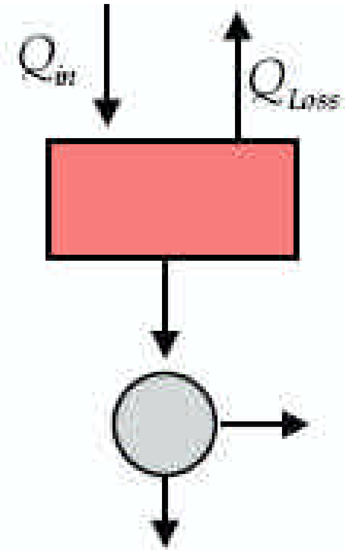
Efficiency:

Radiation to work

$$\eta = \left(\frac{Q_{in} - Q_{Loss}(T)}{Q_{in}}\right)\left(1 - \frac{T_a}{T}\right)$$

||

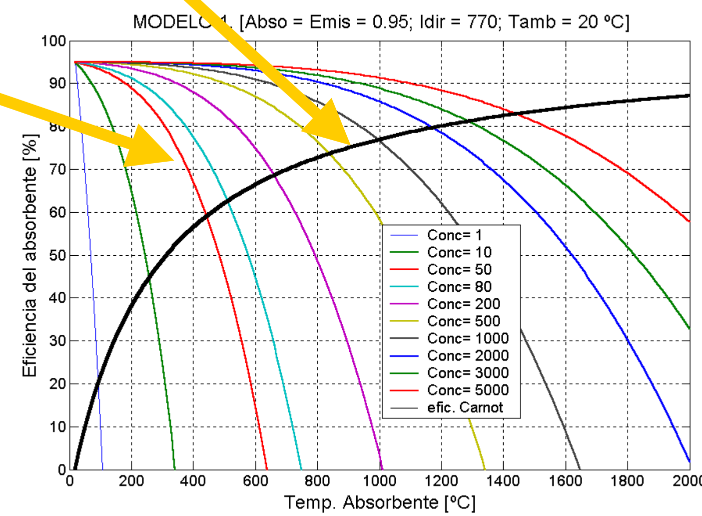
$$h_{rec} = a - s * e * \frac{(T_{abs}^4 - T_{amb}^4)}{Conc * f}$$



- Increase Q_{in} with T fixed, Q_{Loss} fixed
- Increase T with fixed Q_{in}, Q_{Loss}: reduce area

  ⇒ Increase incident flux

$$\frac{Q^*_{gain}}{A} = a * Conc * f - s * e * (T_{abs}^4 - T_{amb}^4);$$



Why Concentration?

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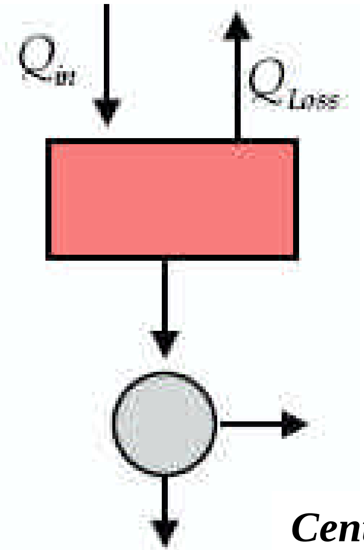


And estimation of the "maximum" Technical efficiency

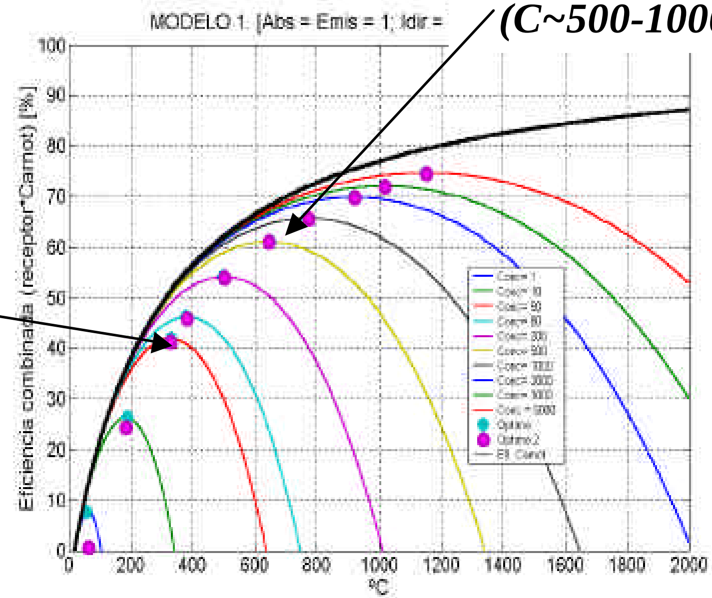
Thus, given:

- The nominal concentration on receiver, and
- The technical cycle

We could choose an "optimal" working temperature

Central Receiver (C~500-1000)

Parabolic Troughs (C ~50)

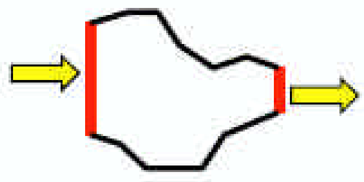


What is Concentration?

Concentration Ratio

$$C_{geom} = \frac{A_{in}}{A_{out}}$$

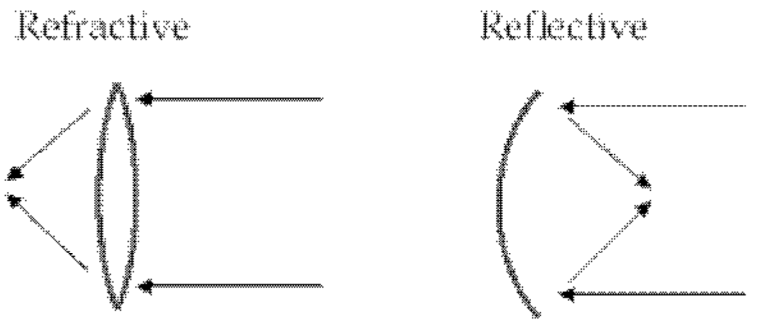
$$C_{flux} = \frac{F_{out}}{F_{in}}$$



Ideal	Real
$E_{in} = E_{out}$	$E_{in} > E_{out}$
$F_{in} A_{in} = F_{out} A_{out}$	$F_{in} A_{in} > F_{out} A_{out}$
$C_{geom} = C_{flux}$	$C_{geom} > C_{flux}$

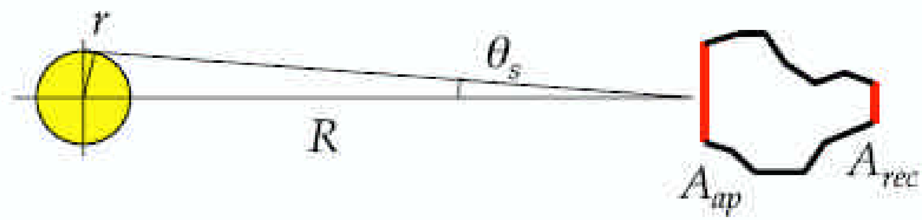
Principle

Redirection of incident light



Intensity: conserved (ideal device) or reduced (real device)

Concentration has a limit



Incident flux: $F_{in} = \sigma T_s^4 \frac{r^2}{R^2}$

Power into aperture: $Q_{sun \to ap} = \sigma T_s^4 \frac{r^2}{R^2} \cdot A_{ap}$

Power emitted from receiver: $Q_{rec} = \sigma T_{rec}^4 \cdot A_{rec}$

Power to sun: $Q_{rec \to sun} = \sigma T_{rec}^4 A_{rec} \cdot f_{rec \to sun}; \quad (f_{rec \to sun} \le 1)$

Ideal concentrator $Q_{rec} = Q_{ap}$

Assume $T_{rec}=T_{sun}$, second law: $Q_{sun \to rec} = Q_{rec \to sun}$

$$\sigma T_s^4 \frac{r^2}{R^2} \cdot A_{ap} = \sigma T_{rec}^4 A_{rec} \cdot f_{rec \to sun}$$

$$\frac{r^2}{R^2} A_{ap} = A_{rec} \cdot f_{rec \to sun} \le A_{rec}$$

Concentration $C = \frac{A_{ap}}{A_{rec}} \le \frac{R^2}{r^2} = \frac{1}{\sin^2 \theta_s}$

Two dimensions:

(Line focus)

$$C = \frac{A_{ap}}{A_{rec}} \le \frac{R}{r} = \frac{1}{\sin \theta_s}$$

Actual limits: $\theta_s = 0.00465 \text{ rad}$

$$C_{3D} \le \frac{1}{\sin^2 \theta_s} \approx 46{,}000$$

$$C_{2D} \le \frac{1}{\sin \theta_s} \approx 215$$

Concentrators:

Parabolic Reflector

Geometry $x^2 = 4Fy$

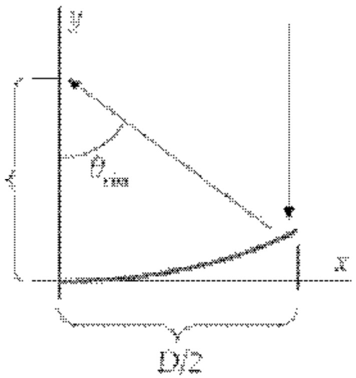
Aperture size D: amount of energy

Focal length F: position of image

Rim angle θ_{rim}: size of image

$$y(x = D/2) = \frac{D^2}{16F}$$

$$\tan\theta_{rim} = \frac{D/2}{F - \frac{D^2}{16F}}$$



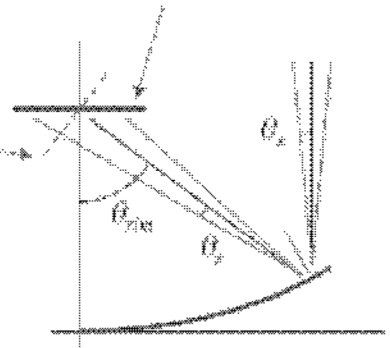
Distance to target $s = \frac{D/2}{\sin\theta_{rim}}$

Radius of image
On perpendicular plane

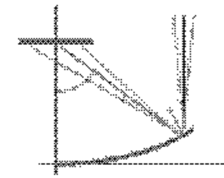
$$r_\perp = s\tan\theta_s \approx s\theta_s$$

Radius of image
On target plane

$$r = \frac{r_\perp}{\cos\theta_{rim}} = \frac{D\,\theta_s}{2\cos\theta_{rim}\,\sin\theta_{rim}}$$



Inlet plane: aperture $D/2$
Outlet plane: target r



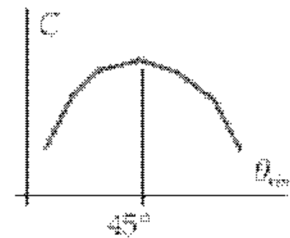
Geometric concentration ratio

$$C = \frac{(D/2)^2}{r^2} = \left(\frac{\cos\theta_{rim}\,\sin\theta_{rim}}{\theta_s}\right)^2$$

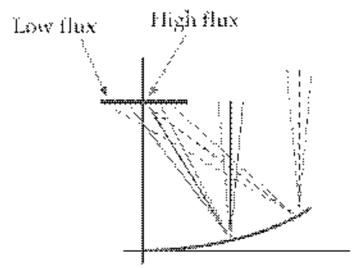
$$C_{max} = \frac{1}{4}\cdot\frac{1}{\theta_s^2} << C_{3D} = \frac{1}{\theta_s^2}$$

In 2-D: $C = \cos\theta_{rim}\,\sin\theta_{rim}/\theta_s$

$$C_{max} = \frac{1}{2}\cdot\frac{1}{\theta_s} < C_{2D} = \frac{1}{\theta_s}$$



With paarbolic concentrator
(3D): Cmax ~46000/4 =11500
(2D): Cmax ~ 215/2 = 110

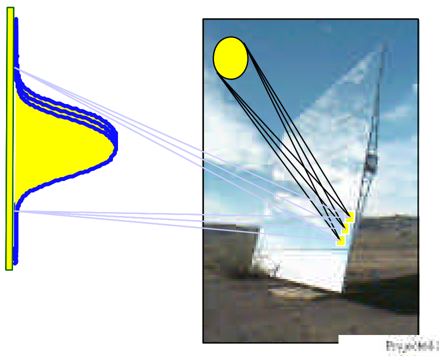


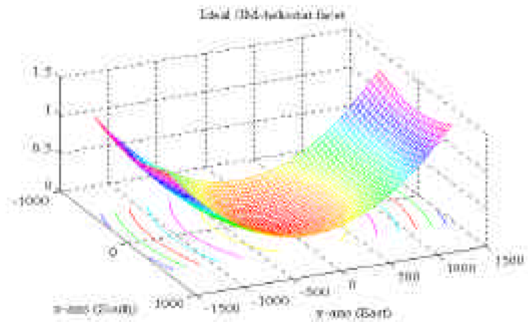
Spread of image sizes
Average concentration: lower than potential

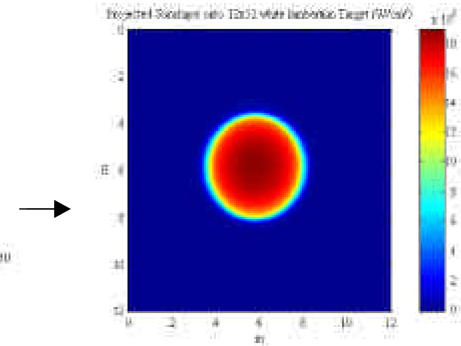
Loss of Concentration ratio

Imperfections

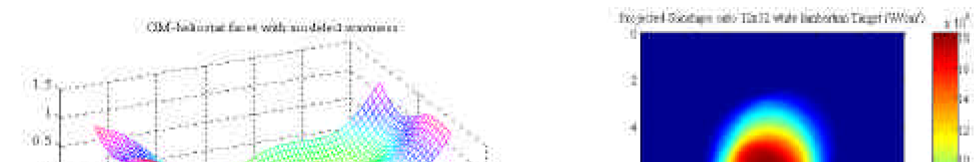
Surface Error



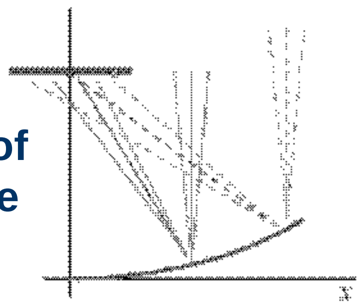


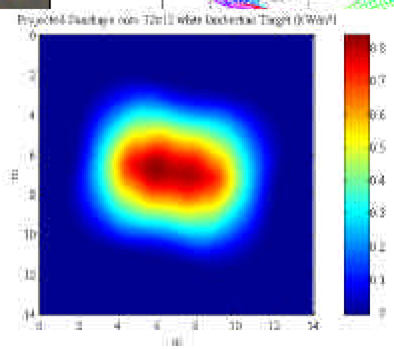


Spherical curvature, no waviness

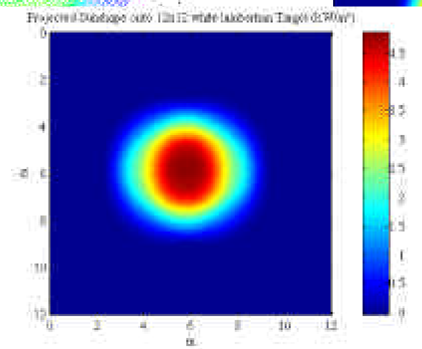


Variability of Focal Image

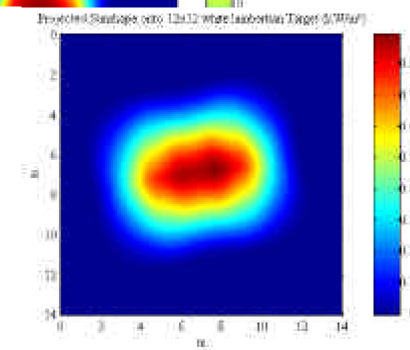




Summer solstice, 7:30 a.m.



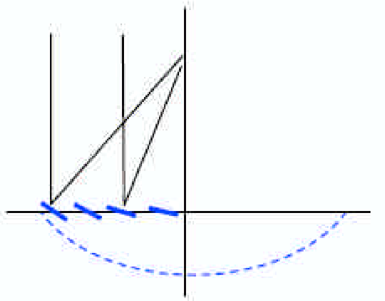
Summer Solstice, solar noon



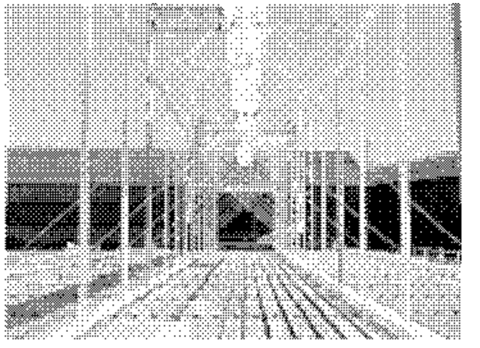
Summer Solstice, 7:30 p.m.

Other Concentrators:

Fresnel Reflector

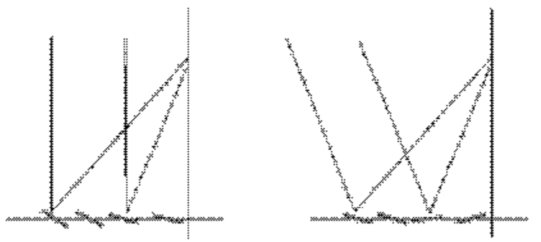


Fragmented reflector
Flat structure
Simulate parabolic or other geometry
Size limit for tracking

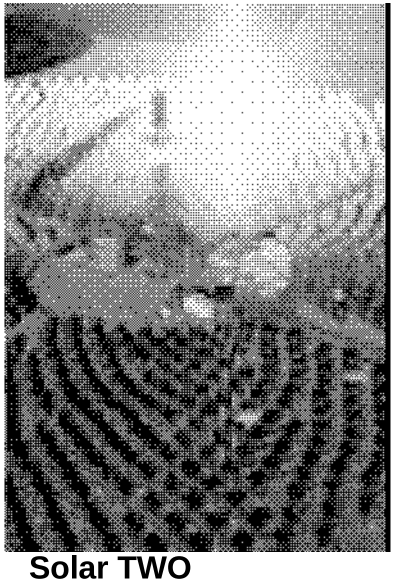


linear Fresnel (Solarmundo)

Heliostat Field



Movable individual mirrors:
Circumvent size limit for tracking



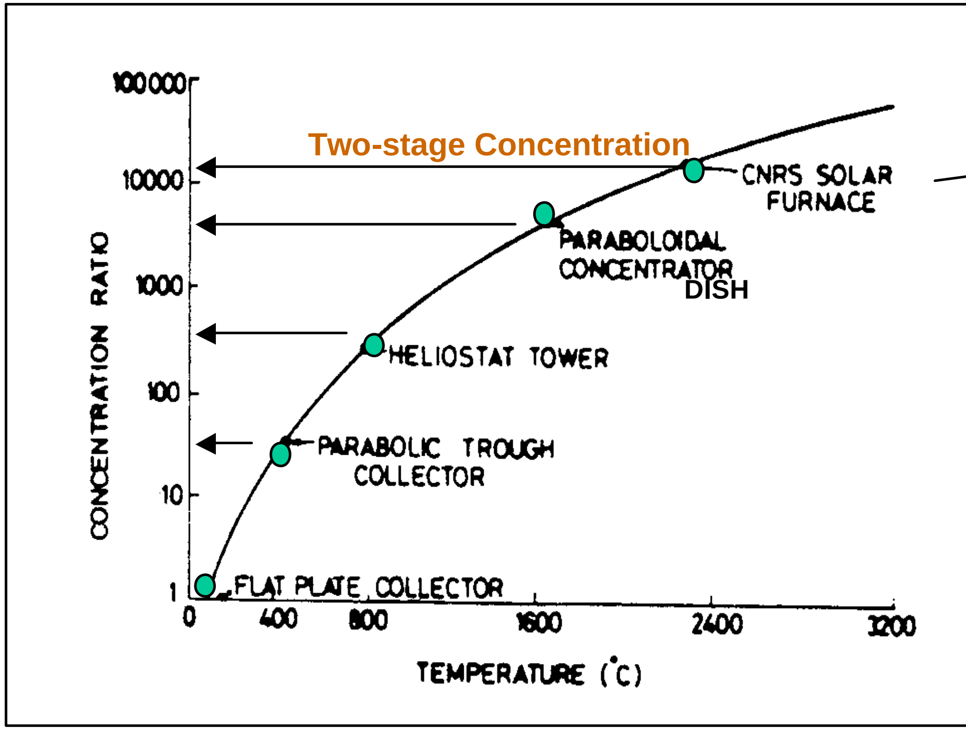
Solar TWO

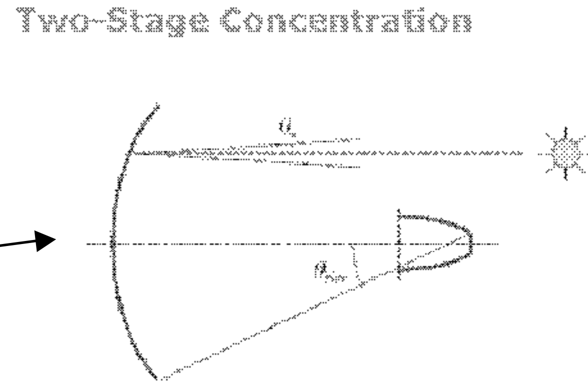
Concentration realistic limit:

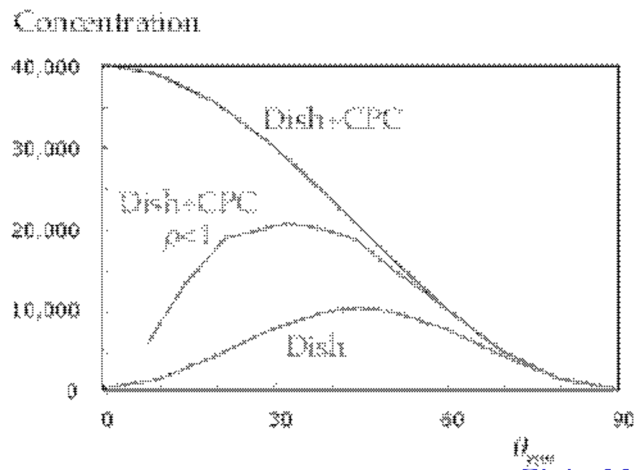
Conc. limit may be higher with different media:

$$Cmáx_{3D} = \frac{n'^2}{n^2 sen^2 q_S}$$

Real concentration systems include imperfections, errors, etc.:

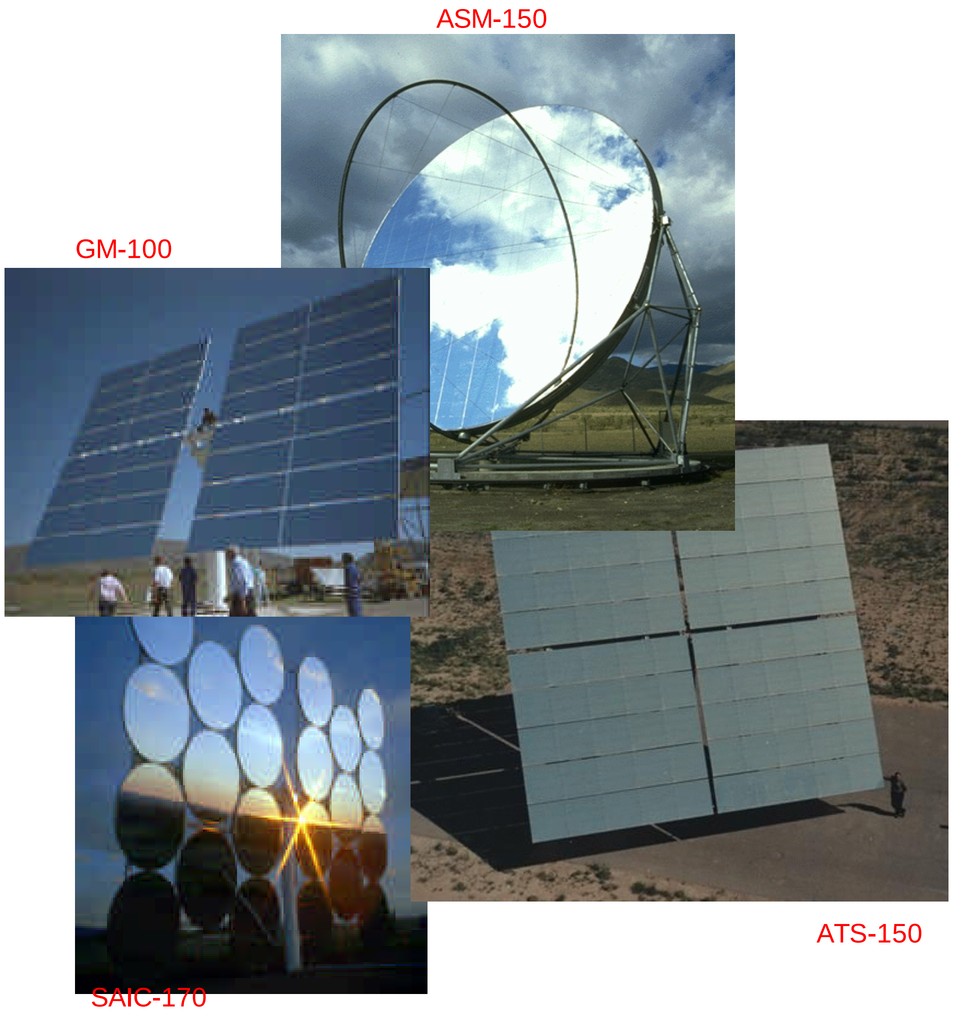






Concentrators Development
Central Receiver

- Heliostat performance is excellent and well-established
- Reducing costs of early builds is needed.
- Reduction of installation and maintenance costs eing tested in PS-10
- Actual sizes ~120 m2
- Actual costs ~240 €/m2 (installed)



Concentrators Development
Parabolic troughs

Concentrators Development
Parabolic Dishes

WGAssociates ADDS

- Stirling Energy Systems
- 25 kW Grid-Tie

- SAIC/STM SunDish System

- EURODISH

- DISTAL

Receivers

Role   Absorb concentrated radiation
        Transfer heat to a working fluid

Operating temperature
- Receiver efficiency
- Further conversion efficiency (exergy)

Heat transfer fluid
- Temperature range
- Corrosion, toxicity, etc.

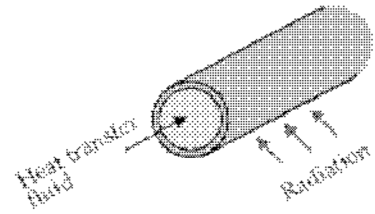
Structural materials
- Temperature, pressure constraints
- Cost

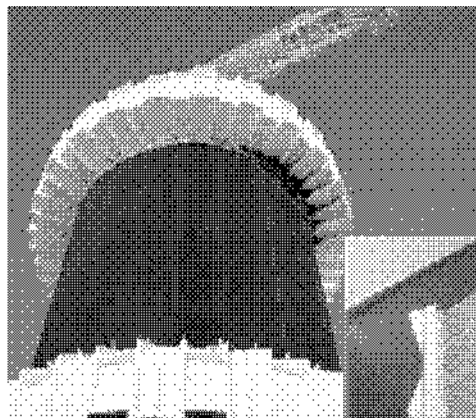
Tubular Receivers

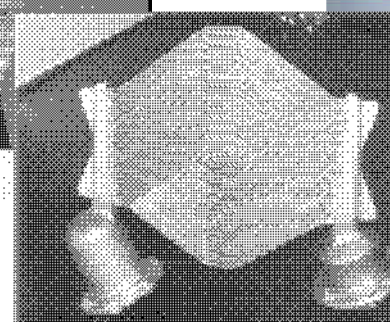
Heat transfer in series:
- Absorption
- Conduction
- Convection

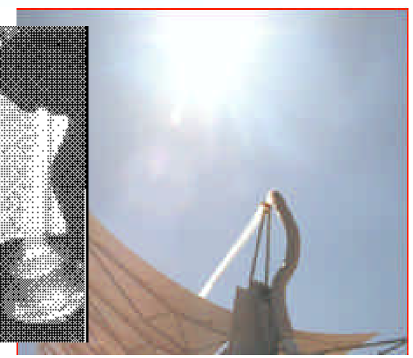
Fluids
- Water / steam
- Air, Helium
- Molten metals, salts

Tube material
- Steel
- Ceramic









Volumetric Receivers

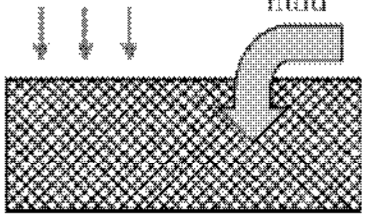
<u>Role</u> Absorb concentrated radiation
Transfer heat to a working fluid

<u>Operating temperature</u>
- Receiver efficiency
- Further conversion efficiency (exergy)

<u>Heat transfer fluid</u>
- Temperature range
- Corrosion, toxicity, etc.

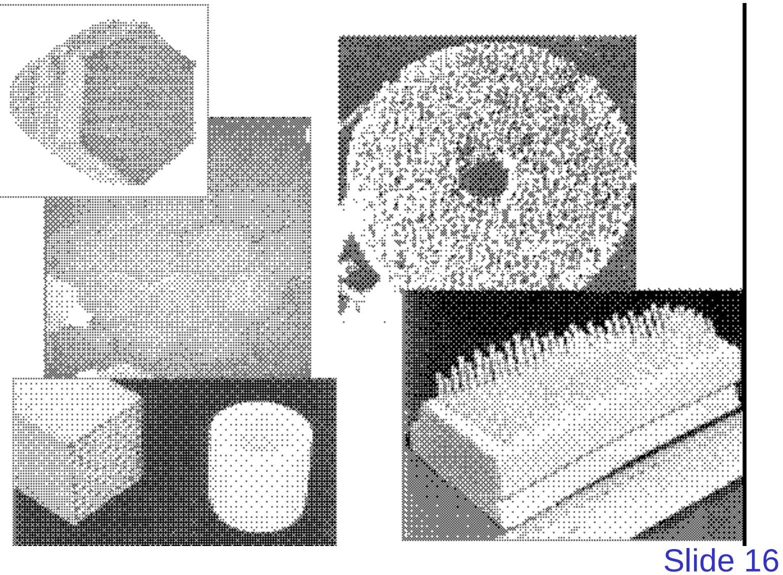
<u>Structural materials</u>
- Temperature, pressure constraints
- Cost

<u>Heat transfer</u> in series:
- Absorption
- Convection

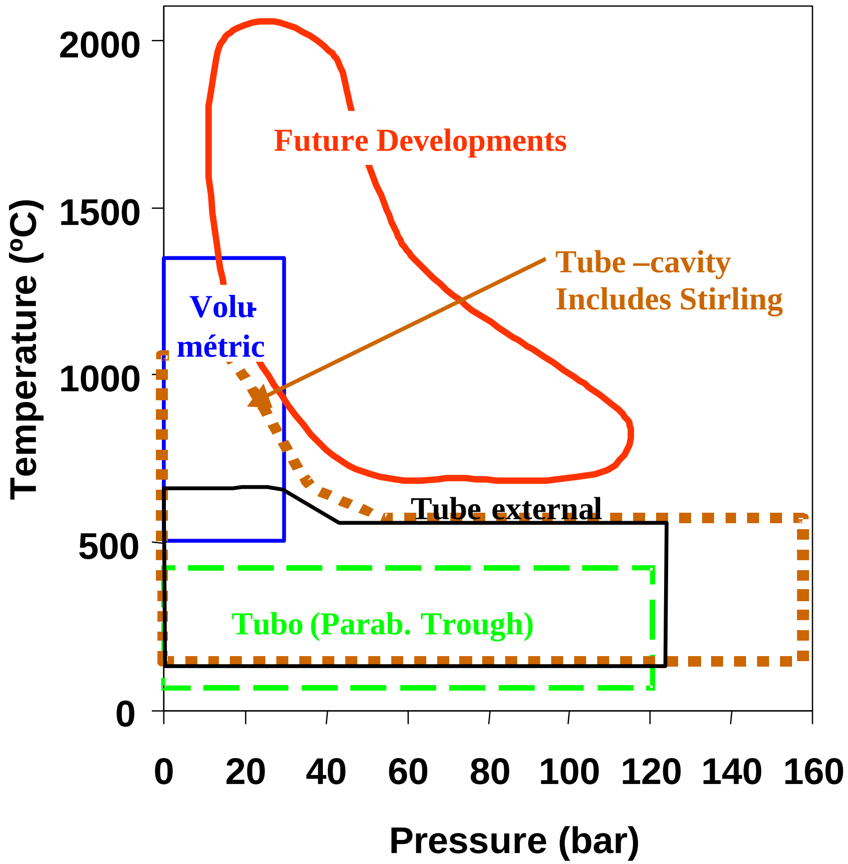


<u>Fluids</u>
- Air
- Other gas: closed

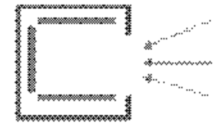
<u>Absorber material</u>
- Steel wire
- Ceramic pellets
- Ceramic foam



Receiver choice



Cavity Receivers



Increase heat transfer area

Keep heat loss low

- Emission, convection: aperture size
- Conduction: insulate
- Reflection: "cavity effect"

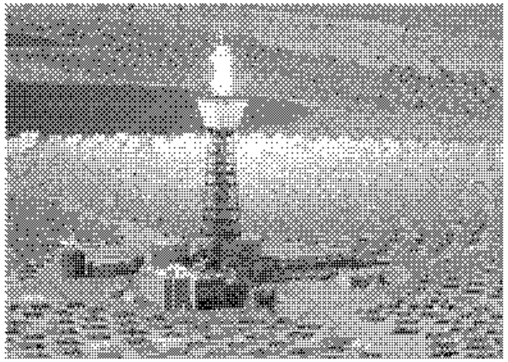
Absorber:

- Tubular
- Volumetric

Example

External tubular receiver

Turbine isentropic efficiency 0.85
Steam temperature 550 K
Optical efficiency 0.7



Incident power: $Q_{in} = \pi DH \cdot CG_b = 10\ \text{MW}$

Lost by reflection: $Q_{ref} = (1-\varepsilon)\, Q_{in} = 0.5\ \text{MW}$

Loss by emission:

$$Q_{em} = \pi D \int_0^H \varepsilon\sigma\left(T_{abs}^4(x) - T_{amb}^4\right) dx$$

$$= \pi DH\varepsilon\sigma\left(\frac{T_{out}^5 - T_{in}^5}{5(T_{out} - T_{in})} - T_{amb}^4\right)$$

$$= 330\ \text{kW}$$

Loss by convection: need convection coefficient correlation

$$(2) \qquad h = \max\left\{5,\ 8.6\frac{v^{0.6}}{L^{0.4}}\right\} = 26\ \frac{\text{W}}{\text{m}^2\text{K}}$$

$$Q_{conv} = \pi D h \int_0^H \left(T_{abs}(x) - T_{amb}\right) dx = 251\ \text{kW}$$

Overall loss and efficiency:

$$Q_{loss} = Q_{ref} + Q_{em} + Q_{conv} = 1081\ \text{kW}$$

$$\eta_{rec} = 1 - \frac{1{,}081}{10{,}000} = 0.89$$

Heat to the steam: $Q_{st} = 8{,}900\ \text{kW}$

Turbine work: $W_T = 0.85 \cdot Q_{st}\left(1 - \frac{300}{550}\right) = 3{,}440\ \text{kW}$

$$\eta_{PCU} = \frac{3{,}440}{8{,}900} = 0.39$$

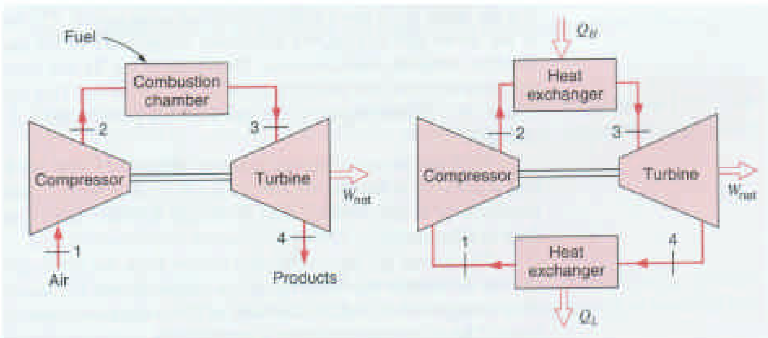
Overall system efficiency: $\eta_{sys} = \dfrac{W_T}{Q_{sol}} = \eta_{opt} \cdot \eta_{rec} \cdot \eta_{PCU}$

$$\eta_{sys} = 0.7 \cdot 0.89 \cdot 0.39 = 0.24$$

* Practical conversion efficiency in solar Rankine plants: 15—20%

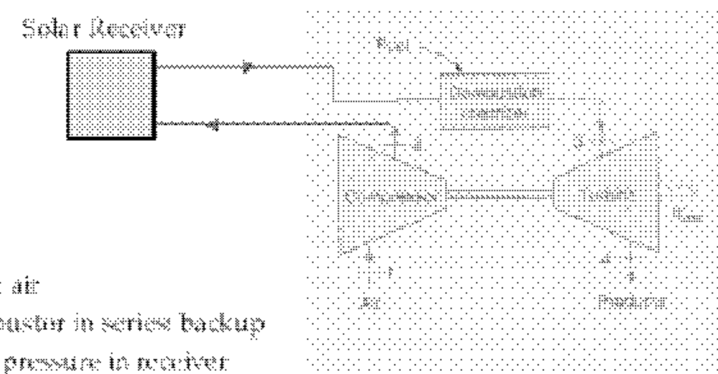
"Solarising" Bryton cycles

Brayton Cycle



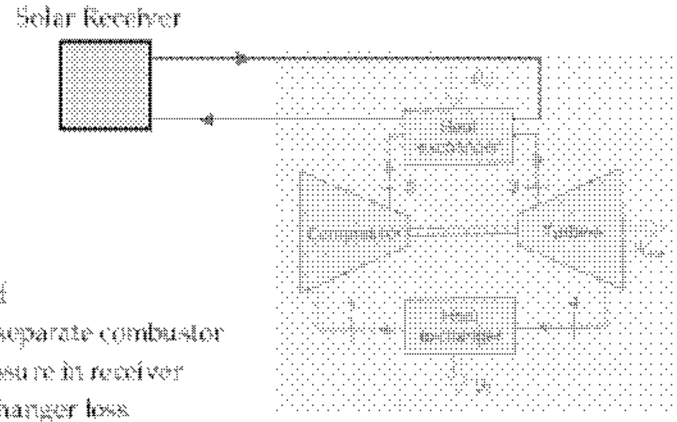
Aero engines, power stations
Simple, reliable, quick start, inexpensive
Efficiency ≤ 35%

Open Solar Brayton



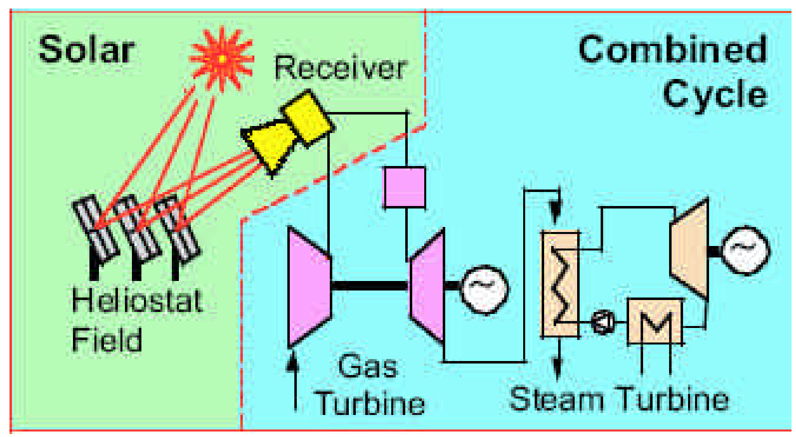
Fluid: air
Combustor in series backup
High pressure in receiver

Closed Solar Brayton

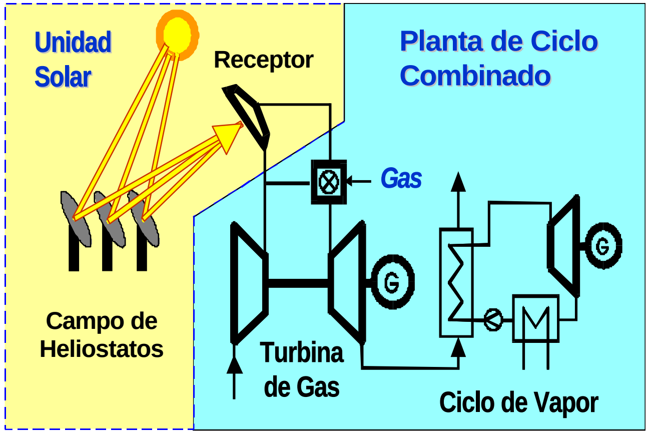


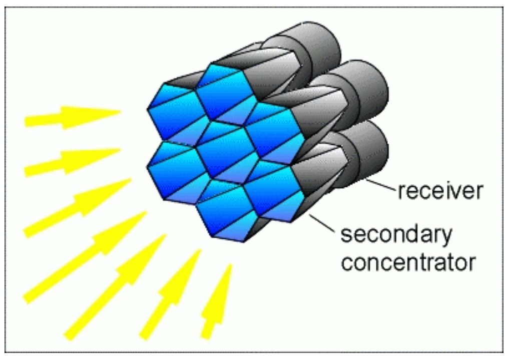
Any fluid
Backup: separate combustor
Low pressure in receiver
Heat exchanger loss
High-temperature heat exchanger

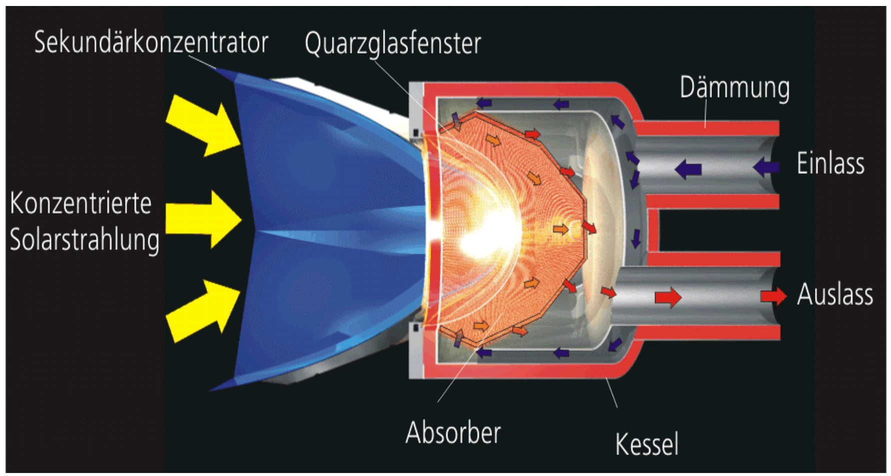
E.g.:Projects:REFOS/SOLGATE/SOLHYCO:



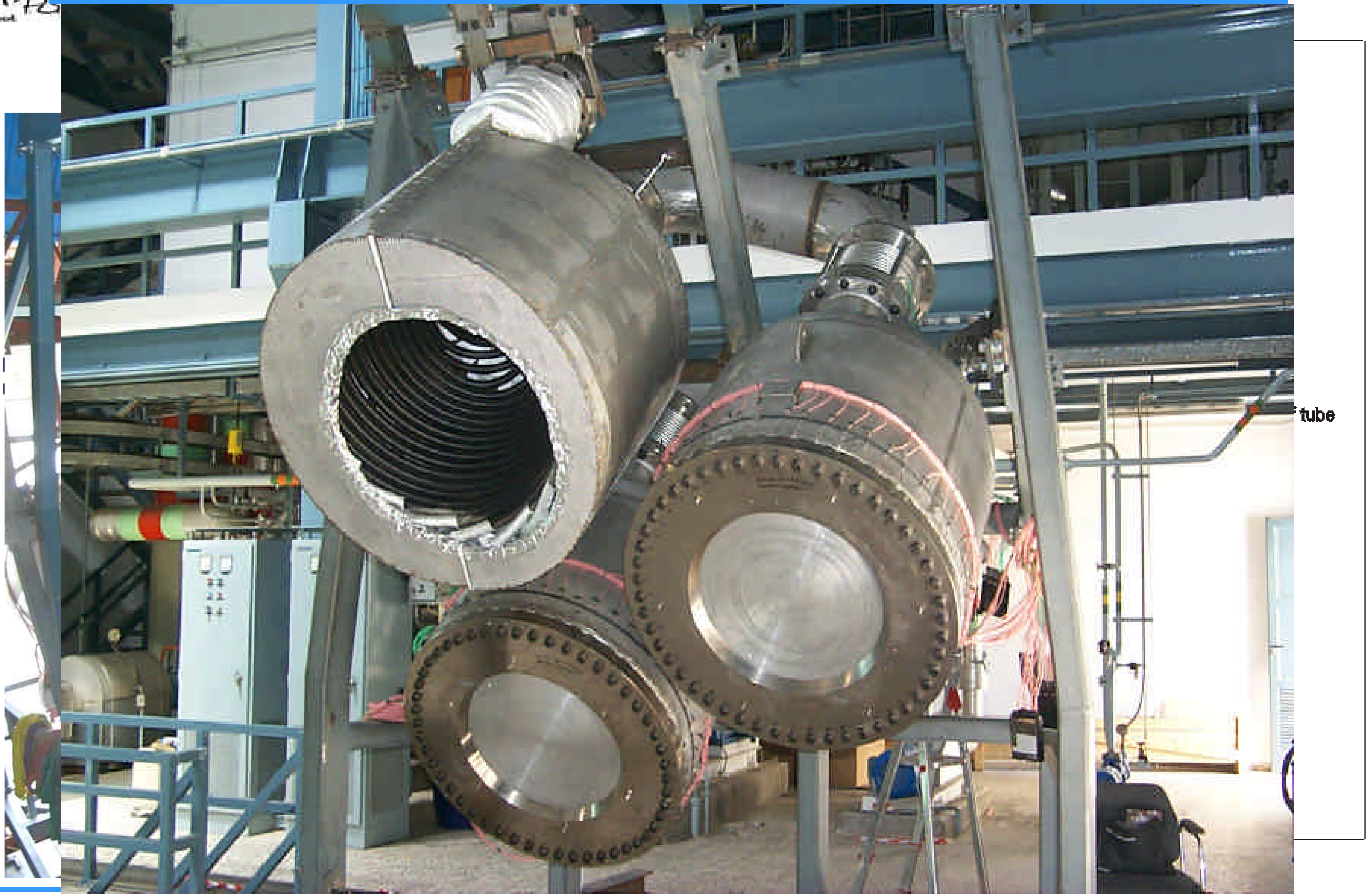
Example of pressurized air technology
Proj.: REFOS,SOLGATE,HST,SOLHYCO…



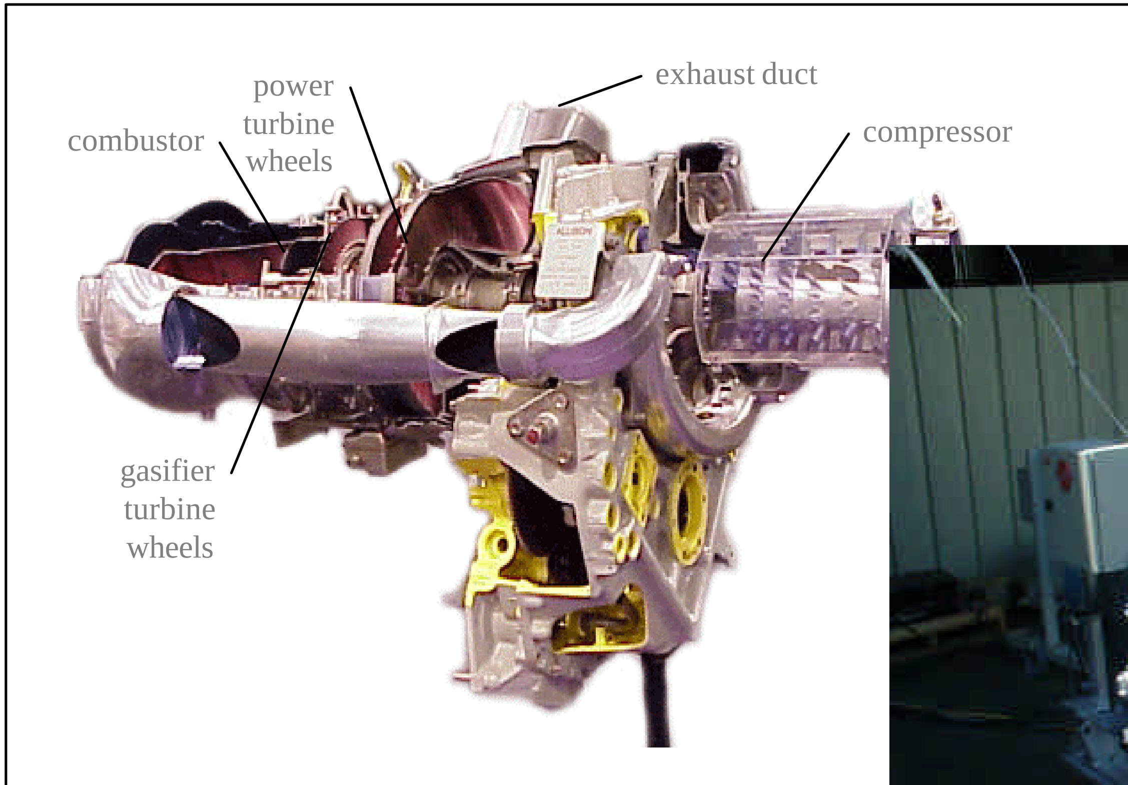


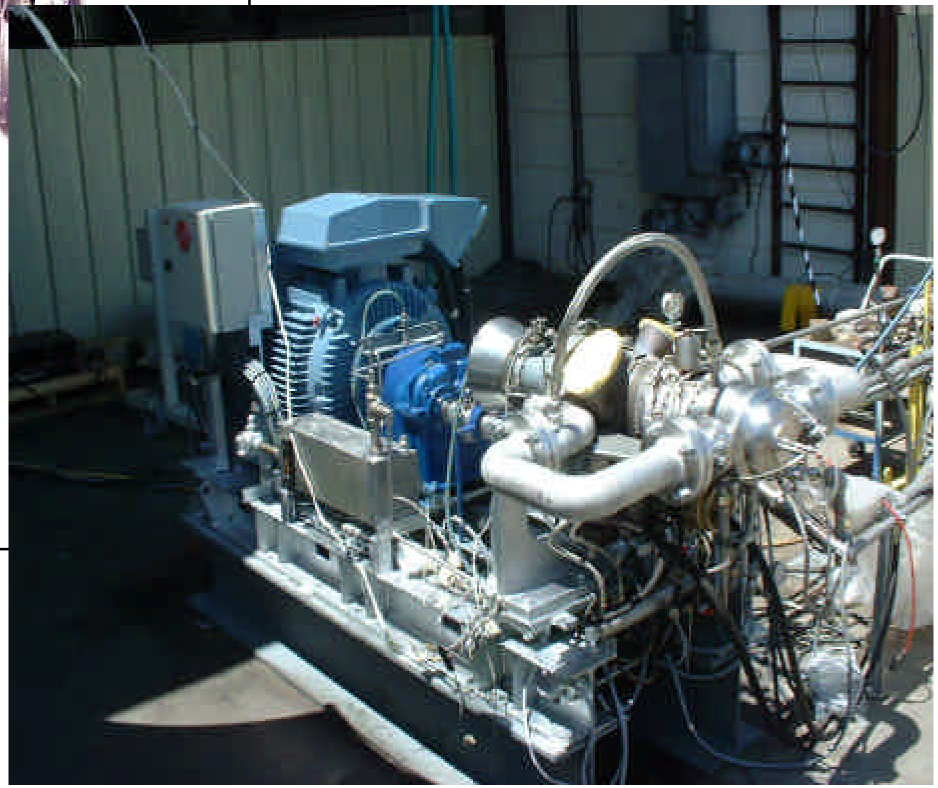


Project SOLGATE



Solarization of an Allison C-20 turbine





Solgate test and Evaluation (2002)

Utilization of solar flux measurements:

- For qualitative diagnostic
- For estimation of the steady-state thermal efficiency of receiver modules and receiver cluster.

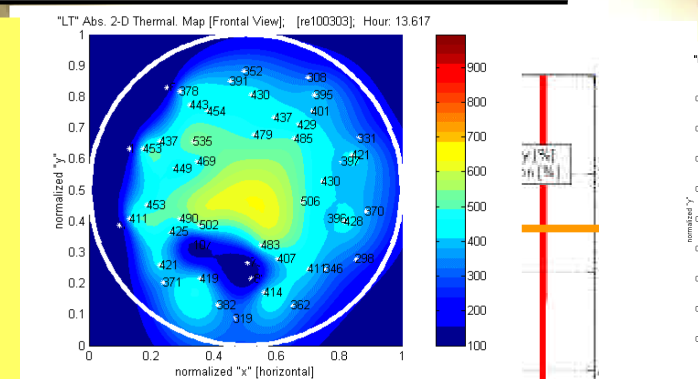


Figure 40.

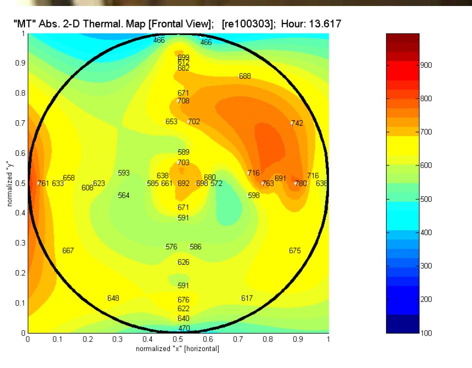


Figure 41

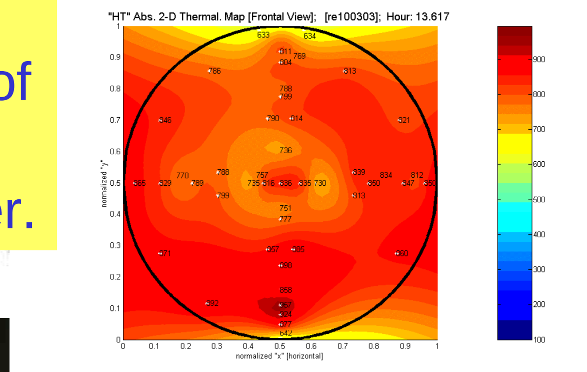
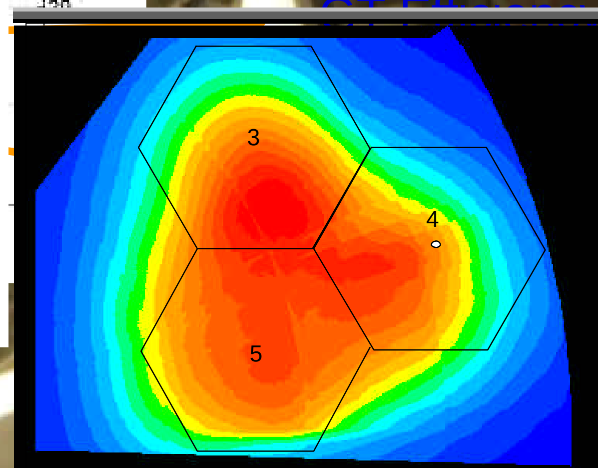


Figure 42

(~ 130 kWe)

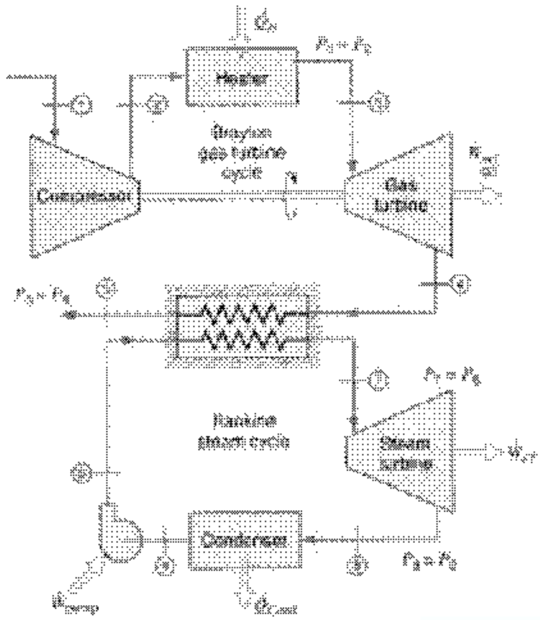


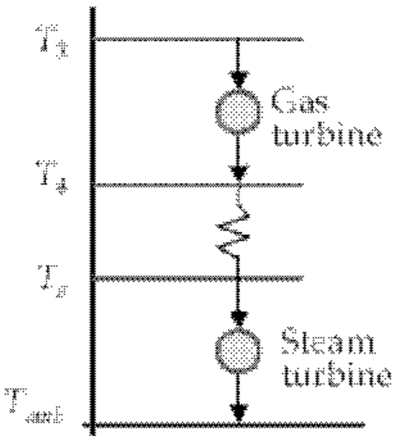
Solar Flux at 13.745 hours

Combined Cycles

Combined Cycle

Residual energy in exhaust air (T_4)





Example: a solar combined cycle

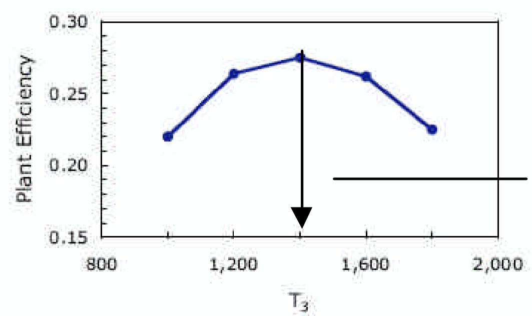
Direct insolation 800 W/m2
Flux concentration on receiver: 2,000
Optical efficiency 0.7
Receiver temperature 1,300 K
Brayton compression, expansion ratio: 10, 9.1
Open Brayton cycle, air (γ=1.4)
Isentropic efficiencies: compressor 0.88, gas and steam turbines 0.85
Ambient temperature 300 K

Total plant efficiency:

$$\eta = \eta_{opt} \cdot \eta_{rec} \cdot \eta_{BCU}$$

$$= 0.7 \cdot 0.90 \cdot \frac{516.9 - 317.3 + 96.7}{682.7}$$

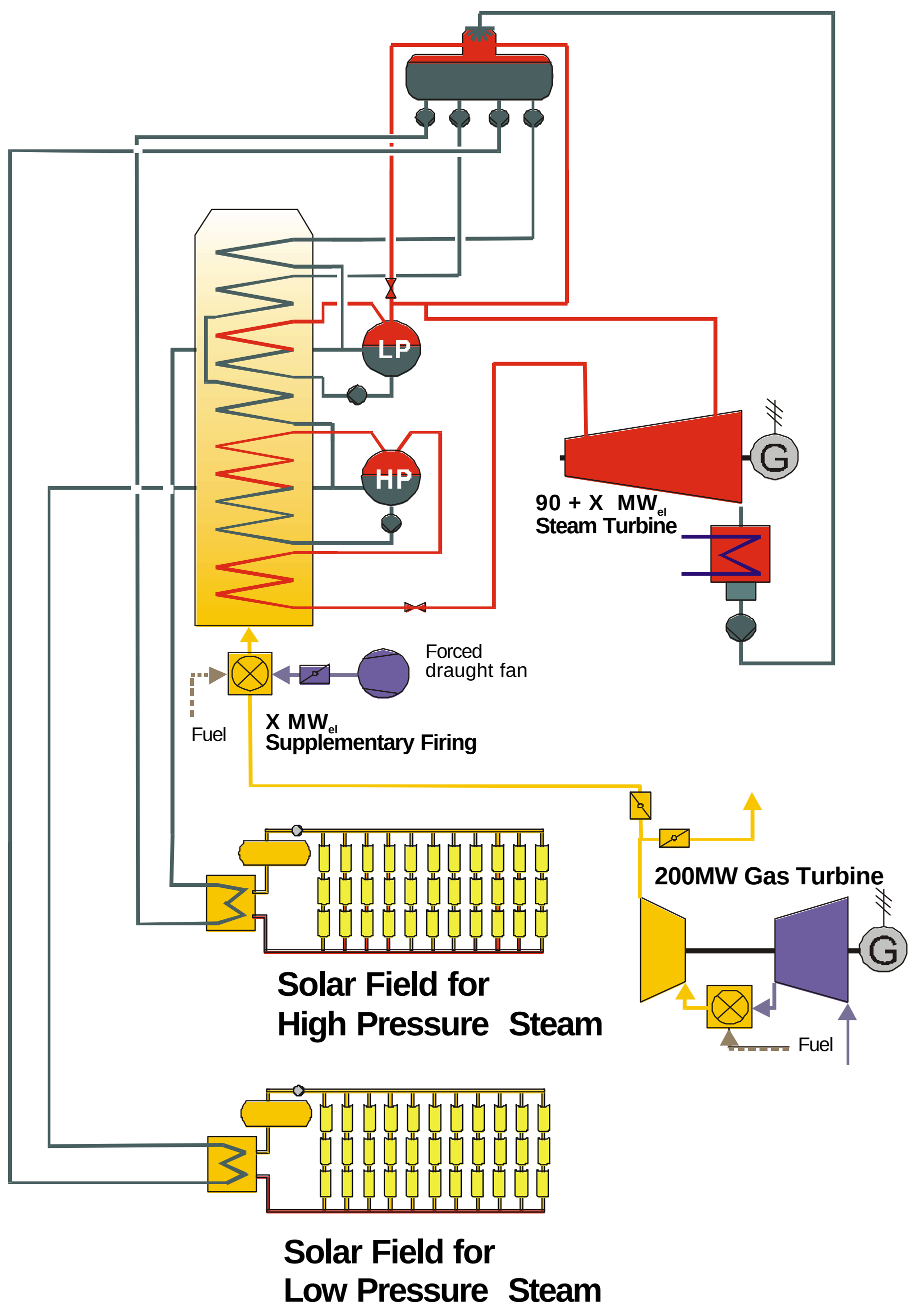
$$= 0.273$$



Challenge:
Materials for high temperature
(& at acceptable costs)

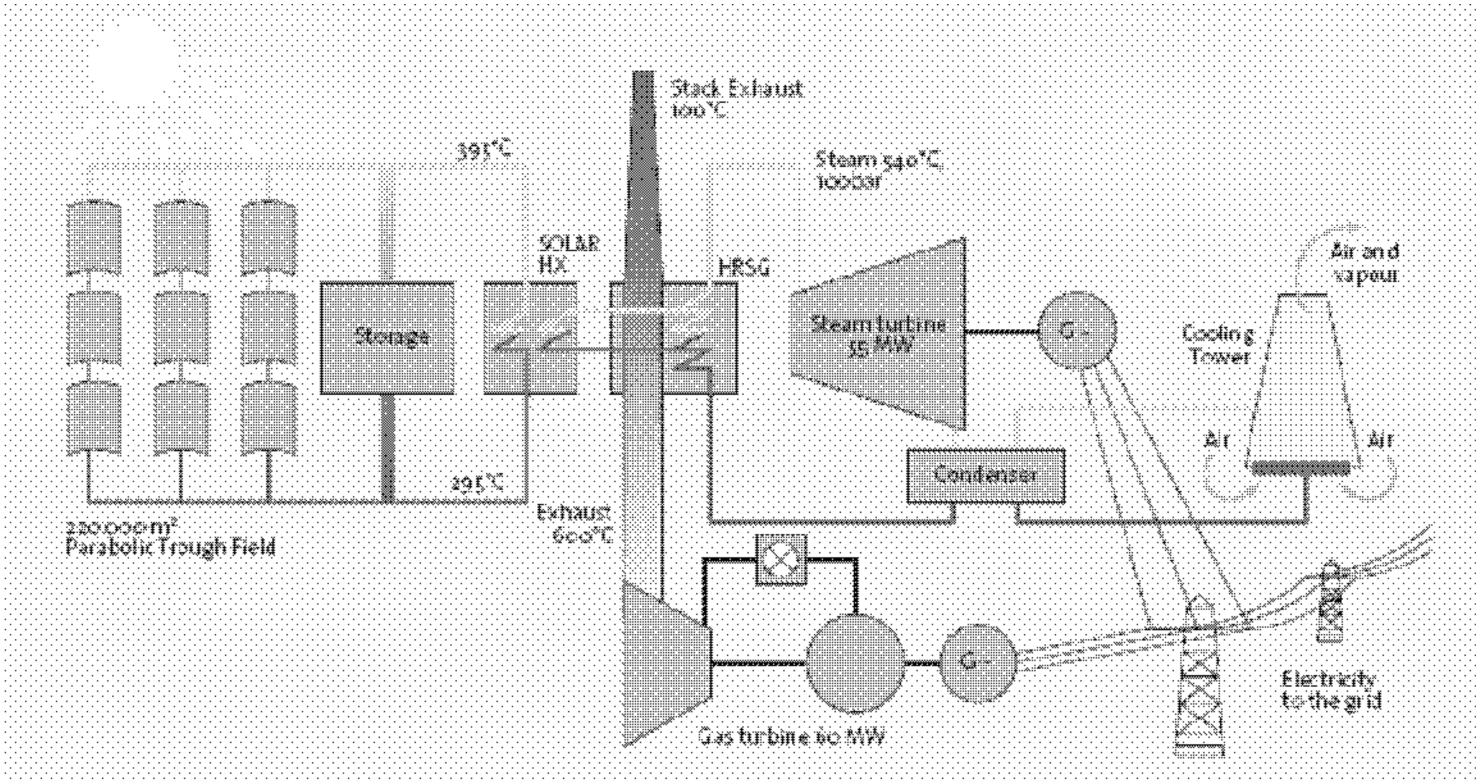
Other parameters:
Concentration
Pressure ratio

International SPP Projects are seeking Support from the **Global Environmental Facility (GEF)** in the framework of Operational Program No.7



The **ISCCS Concept**

Integrated Solar /Combined Cycle System (ISCCS) concept

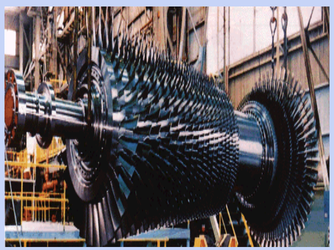


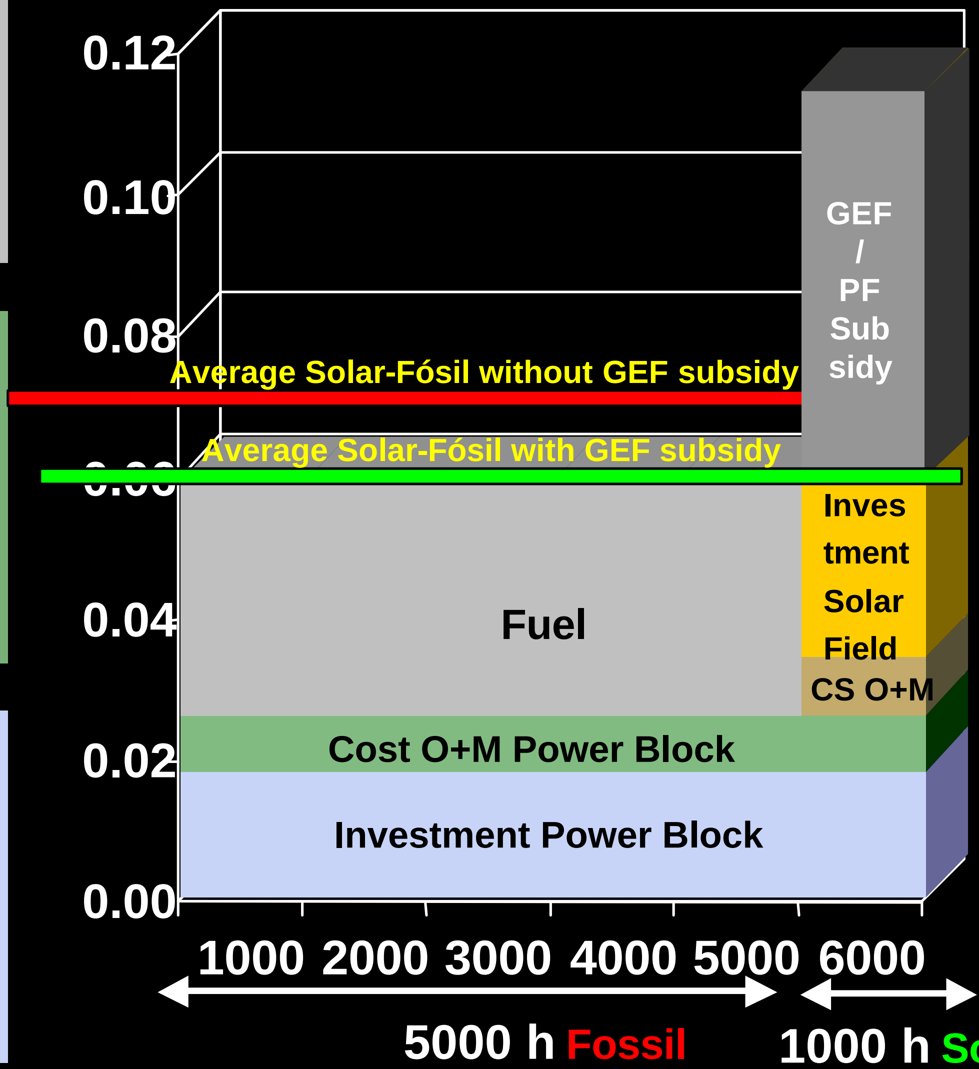
LEC Solar and Fossil in EURO/kWh

Fuel cost

O+M Cost
Conventional part

IOnvestment
Parte convencional



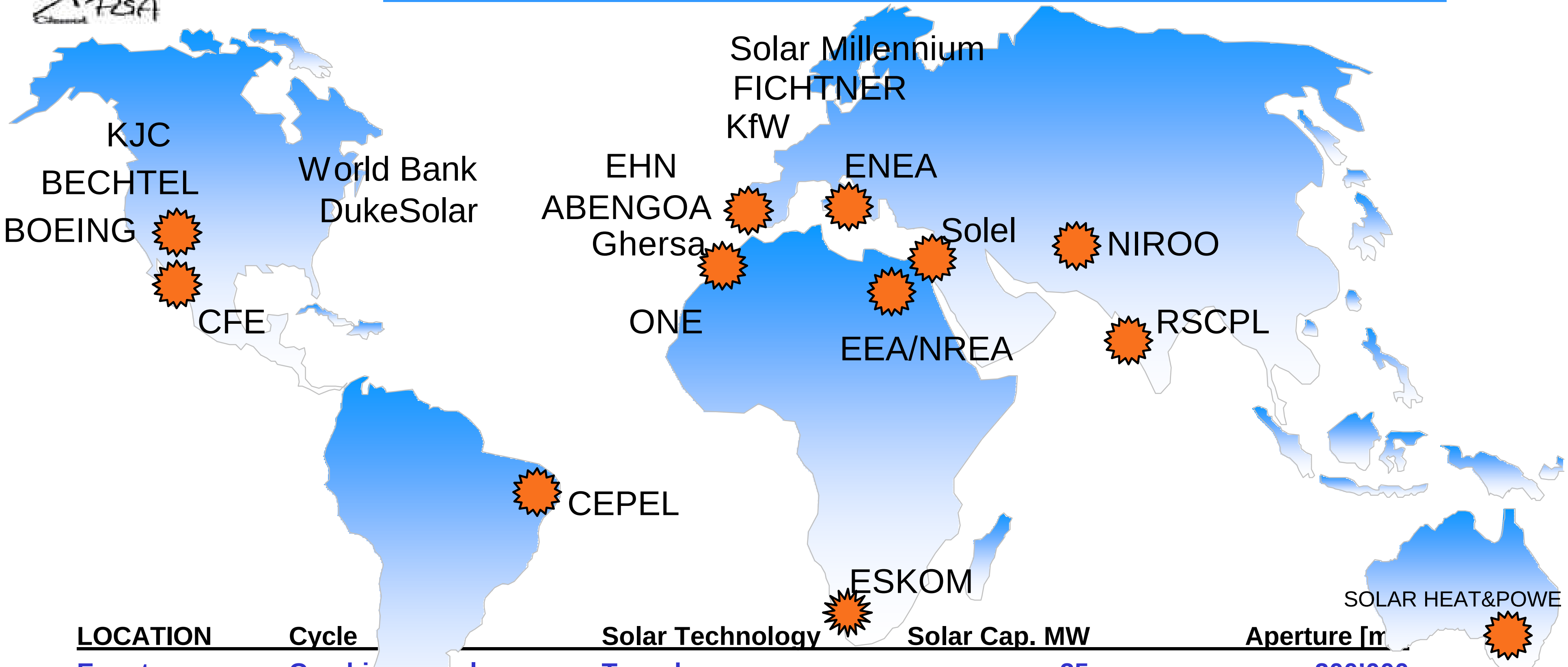


Subsidies

Coste capital
Campo solar

O+M Solar Field

Update of STPP initiatives



LOCATION	Cycle	Solar Technology	Solar Cap. MW	Aperture [m
Egypt	Combined Cycle	Trough	35	200’000
India	Combined Cycle	Trough	35	200’000
Mexico	Combined Cycle	Investor’s Choice	>25	200’000
Australia	Combined Cycle	CFLR	25	120’000
South Africa	Steam Cycle	Tower	100	?
USA	Steam Cycle	Trough	50	?
Israel	Steam Cycle	Trough	100	500’000
Spain	Steam Cycle	Trough (Andasol)	50	549’360
Spain	Steam Cycle	Tower (*PS10*)	10-11	88’290
Spain	Steam Cycle	Tower (*Solar Tres*)	15-17	240’000
Italy	Steam Cycle	Trough (Molten salt)	40	451’215
Argelia ..				
Marruecos ..				

110 ºC

- SEGS experience: SEGS systems co
  O&M costs have decreased 30% with 1
- DISS project: Direct Steam Generation demonstrated at a 1.8 MW test facility with more than 4000 hours at 400ºC, 100 bar and 1kg/s. The expected benefit is a 26% reduction in the electricity cost.
- EUROTROUGH: European project to develop an economical design of parabolic trough collector for electricity production and industrial process heat.

Update of STPP projects under development

Name/Location	Total Capacity (MWe)	Solar Capacity (MWe)	Cycle	Companies/Funding
Parabolic Troughs				
Algeria	140	35	ISCC	New Energy Algeria
Liddell Power Station, NSW, Australia	2000	50	Compact Linear Fresnel Reflector	Macquarie Generation and Solar Heat and Power
Kuraymat, Egypt	150	30	ISCC	NREA / GEF grant, JBIC loan
THESEUS – Crete, Greece	50	50	Steam cycle	Solar Millennium, Flabeg Solar Int., Fichtner Solar, OADYK
Mathania, India	140	30	ISCC	RREC (Rajasthan Renewable Energy Authority) / GEF grant, KfW loan
Yazd / Iran	467	17	ISCC	Mapna / Iranian Ministry of Energy
Israel	100	100	Steam Cycle with hybrid fossil firing	Israeli Ministry of National Infrastructure with Solel
Italy	40	40	Steam Cycle	ENEA
Baja California Norte, Mexico	291	30	ISCC	Open for IPP bids GEF grant
Ain Beni Mathar, Morocco	220	30	ISCC	ONE / GEF grant, African Development Fund
Spain	12x50	12x50	Steam Cycles with 0.5 to 12 hours storage for solar-only operation with 12-15% hybrid firing	Abengoa ACS-Cobra, EHN-Solargenix, Iberdrola, HC-Genesa, Solar Millennium
Nevada, USA	50	50	SG-1 SEGS	Green pricing, consortium for renewable energy park Sierra Pacific Resources with SolarGenix
Central Receivers				
Spain Solar Towers with Steam Receivers PS10 and PS20	10 + 2x20	10 + 2x20	Steam Cycle with saturated steam receiver and steam drum storage	Abengoa (Spain) group
Spain Solar Towers with molten-salt receivers	15	15	Molten-salt/direct-steam	SENER (Spain)
Parabolic Dishes				
SunCal 2000, Huntington Beach California, USA	0.4	0.4	8-dish/Stirling system	Stirling Energy Systems
EuroDish Demonstrations	0.1	0.1	6-dish/Stirling system	SBP and Partners


EuroSEGS
Solar Tres
PS10
AndaSol
OCÉANO ATLÁNTICO
Mar Cantábrico
FRANCIA
ESPAÑA
P E N Í N S U L A
I B É R I C A
Mar Mediterráneo
Mar de Alborán
ARGELIA
MARRUECOS
MINHO
ALENTEJO
A Coruña
Lugo
Santiago de Compostela
Vigo
Ourense
León
Burgos
Palencia
Benavente
Zamora
Valladolid
Soria
Vitoria-Gasteiz
Donostia-San Sebastián
Logroño
Zaragoza
Huesca
Lleida
Barcelona
Tarragona
Girona
Andorra la Vella
Oporto
Braga
Bragança
Aveiro
Coimbra
Viseu
Salamanca
Segovia
Ávila
Madrid
Toledo
Cuenca
Teruel
Castellón de la Plana
Valencia
Palma de Mallorca
Albacete
Gandia
Alcoy
Benidorm
Alicante
Elche
Murcia
Cartagena
Lorca
Lisboa
Évora
Mérida
Beja
Córdoba
Sevilla
Huelva
Faro
Jaén
Linares
Granada
Baza
Almería
El Ejido
Málaga
Ceuta
Argel
Blida
Toulouse
Montpellier
Marsella
Perpiñán
Golfo de León
Nîmes
Tarbes
Pau
Carcasona
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PS10: This 10-MWe solar-only power tower plant project Planta Solar 10 at Sanlúcar near Sevilla is promoted by Solucar S.A., part of the Spanish Abengoa Group. It features application of Phoebus volumetric air receiver/energy storage technology.

Solar Tres: The 15-MWe solar-only power tower plant project at Cordoba is promoted by the Spanish Ghersa and Boeing with application of US molten-salt technologies for receiver and energy storage. Ghersa and Boeing have formed a company in Spain called Solar Tres to finance and build a fully commercial 15 MWe solar power tower plant that can deliver this power around the clock thanks to 16-hour thermal storage

EuroSEGS: The 15-MWe solar trough power plant at Montes de Cierzo near Pamplona is promoted by the Spanish EHN group in cooperation with DukeSolar, making use of improved LS-2 technology and Duke parabolic troughs.

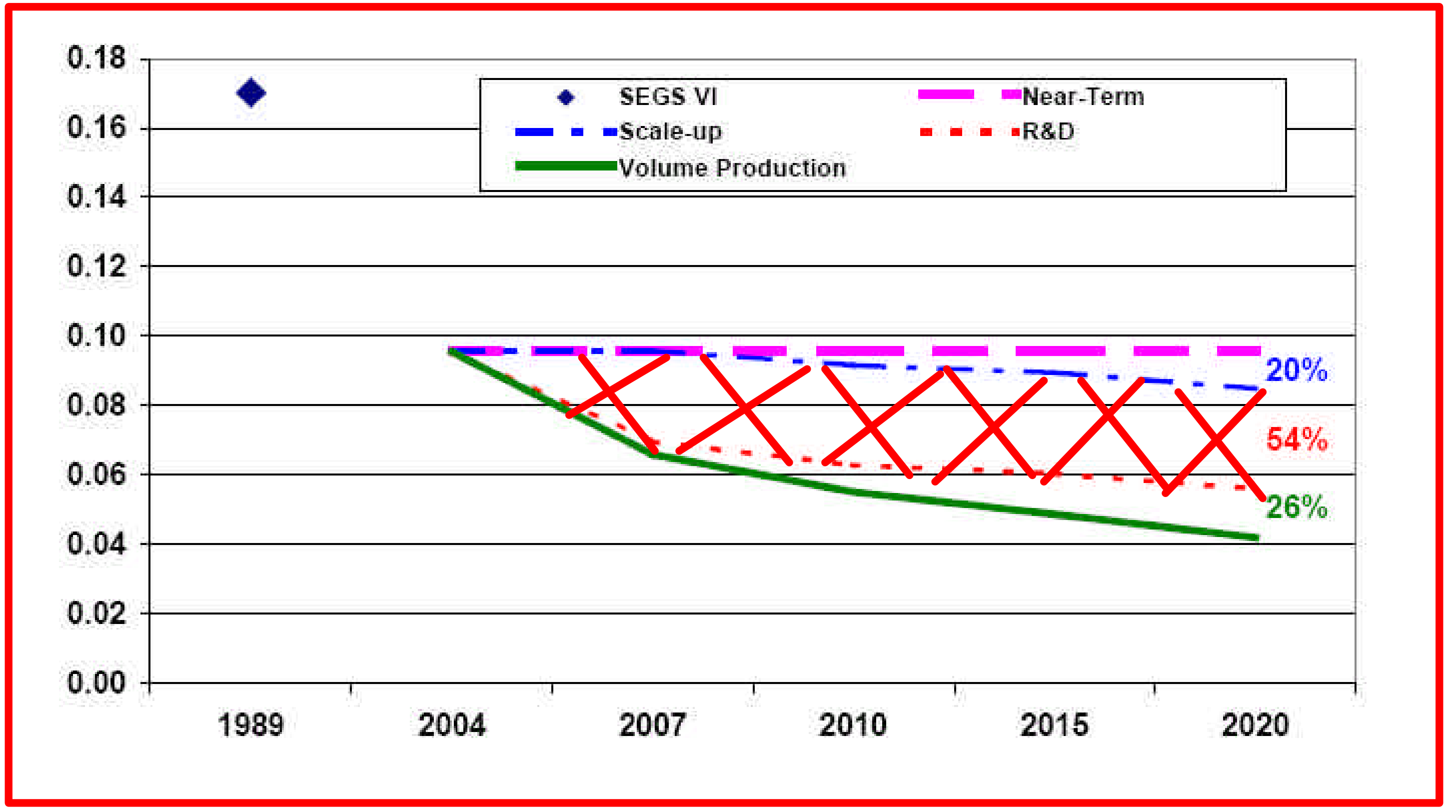
AndaSol: This 50-MWe solar trough power plant near Guadix (Granada) will have a 549,000 m^2 EUROtrough solar collector field and a 9-hour thermal storage. It is promoted by Milenio Solar S.A.

STPP initiatives for Spain

Project Name		PS-10	Solar Tres	AndaSol	EuroSegs
IPP		SANLUCAR SOLAR	SOLAR TRES	MILENIO SOLAR	EHN
EPC		SOLUCAR	GHERSA	Solar Millennium	EHN
Location		Seville Province	Cordoba Province	Granada Province	Navarra Province
Technology		Open Air Tower	Molten Salt Tower	EuroTrough	LS-2 and DS-1 Troughs
Solar field size	m^2	89,271	263,600	549,360	95,880
Storage Capacity (Full load hours)	h	1	16	9	0
Annual DNI	kWh/m^2	≈ 2,000	≈ 2,000	≈ 2,000	≈ 1,700
Turbine rating (gross)	MW	11	15	50	15
Annual Capacity Factor	%	22	63	41	15
Annual solar electricity output (net)	GWh	19.2	84	181.7	20
Investment Cost	Mio €	**36**	**100**	**240**	**45**

Cost reduction potential of CSP

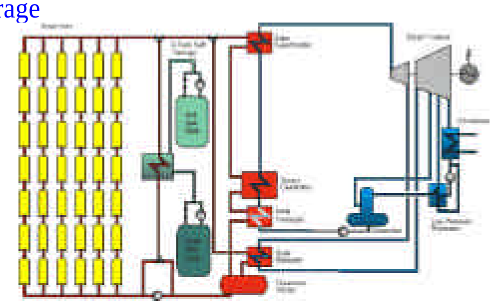
European Concentrated Solar Thermal Road-Mapping



Systems under investigation (ECOSTAR Roadmap)

Reference Systems

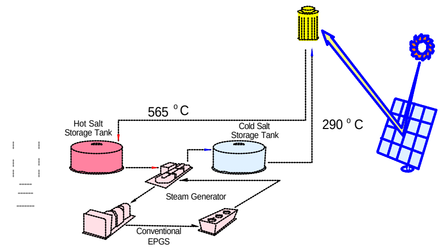
- Parabolic trough plant with HTF Fluid and molten salt storage



ECOSTAR: Overview & Methodolgy

Reference Systems

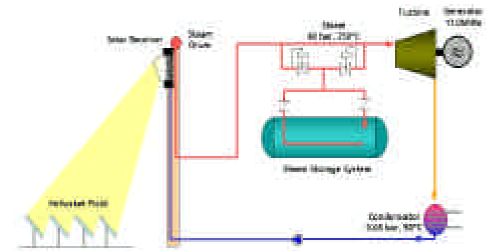
- CRS with molten salt receiver and storage



ECOSTAR: Overview & Methodolgy

Reference Systems

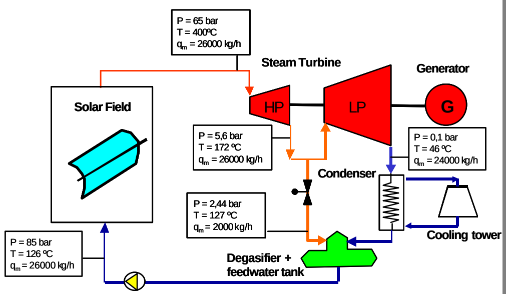
- CRS with saturated steam receiver and rankine cy



ECOSTAR: Overview & Methodolgy

Reference Systems

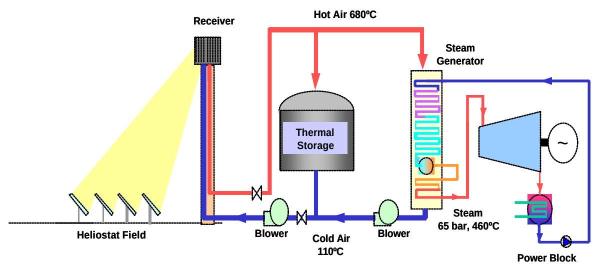
- Parabolic trough plant with DSG (INDITP)



ECOSTAR: Overview & Methodolgy

Reference Systems

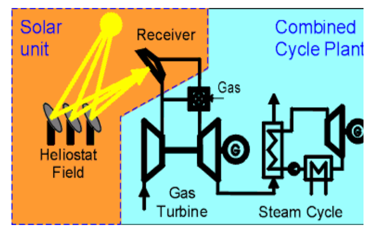
- CRS with air volumetric receiver and rankine cycle



ECOSTAR: Overview & Methodolgy

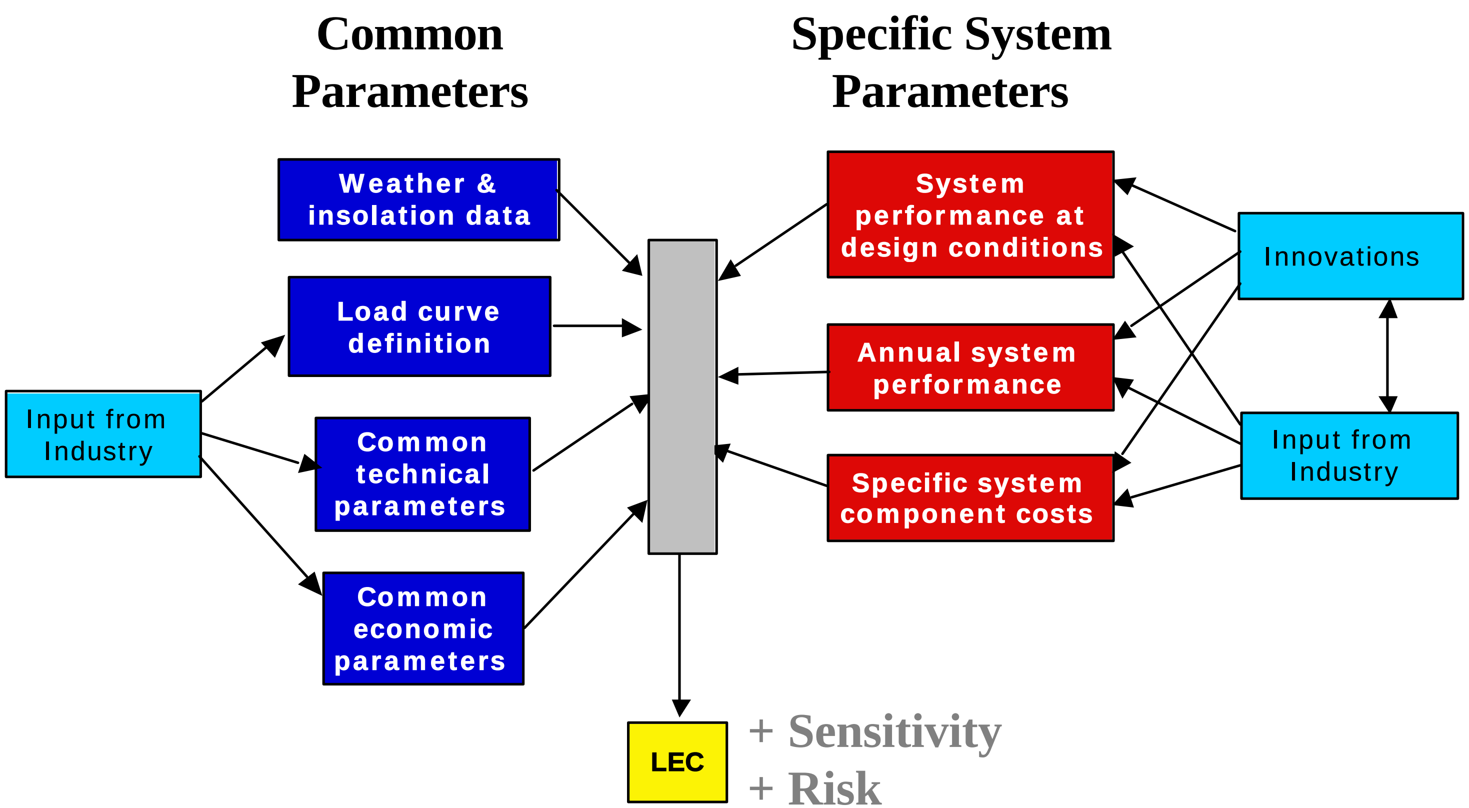
Reference Systems

- CRS solar hybrid gas turbine system

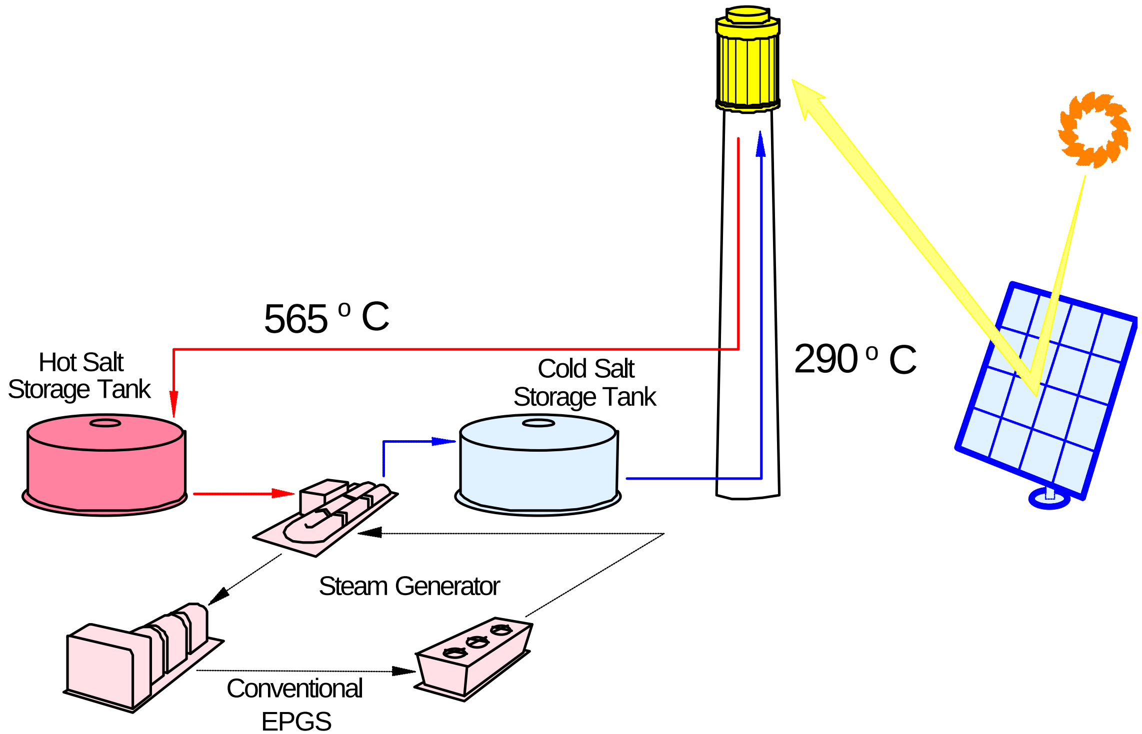


ECOSTAR: Overview & Methodolgy

Methodology Approach



Plant scheme



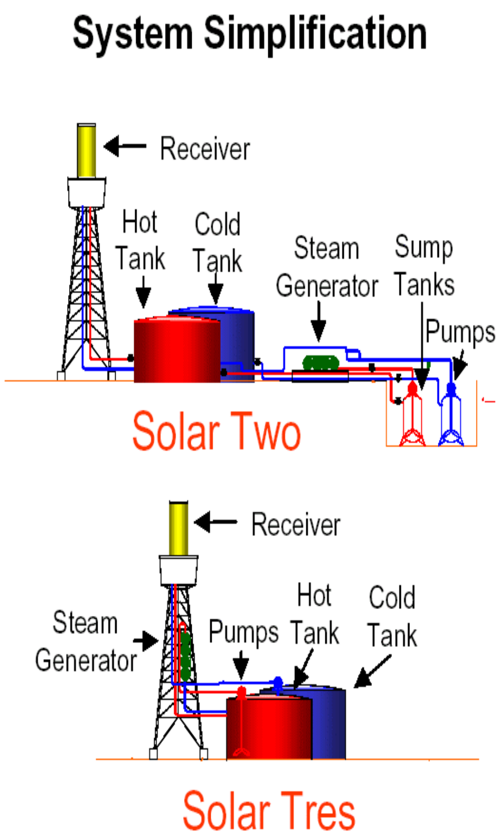
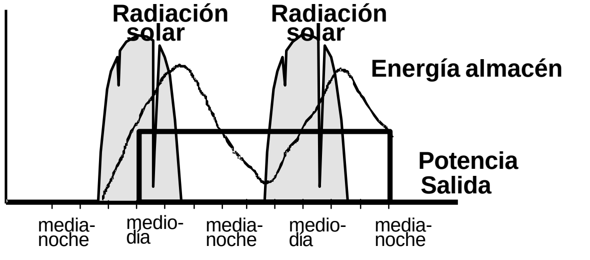


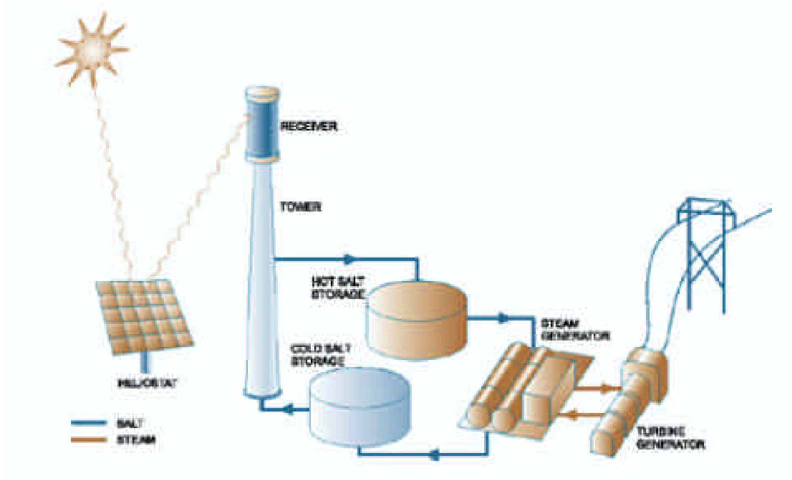
Photo or artists view of the plant and main components

State of the art

- The largest demonstration of a molten salt power tower was the Solar Two project - a 10 MW power tower located near Barstow, CA.
- The plant began operating in June 1996. The project successfully demonstrated the potential of nitrate salt technology.
- Some of the key results were: the receiver efficiency was measured to be 88%, the thermal storage system had a measured round-trip efficiency of greater than 97%, the gross Rankine-turbine cycle efficiency was 34%, all of which matched performance projections.
  - The overall peak-conversion efficiency of the plant was measured to 13.5%. The plant successfully demonstrated its ability to dispatch electricity independent of collection. On one occasion, the plant operated around-the-clock for 154 hours straight.
  - the project identified several areas to simplify the technology and to improve its reliability. On April 8, 1999, this demonstration project completed its test and evaluations and was shut down.



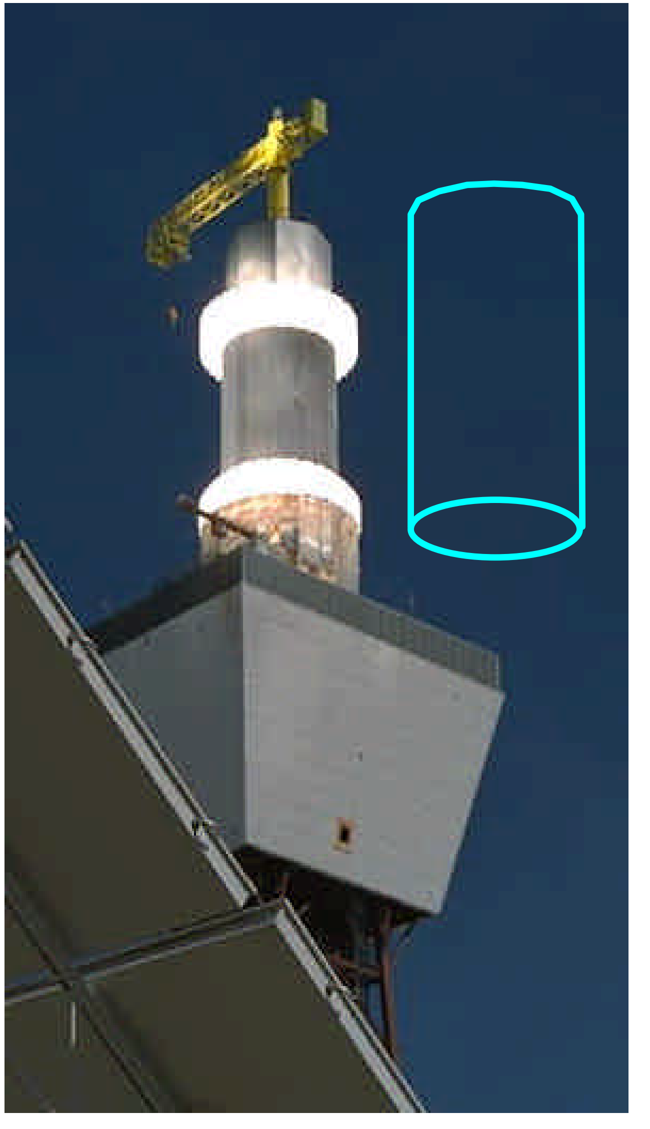
Solar Two – Solar TRES



Solar Two: Tube receiver with molten salt

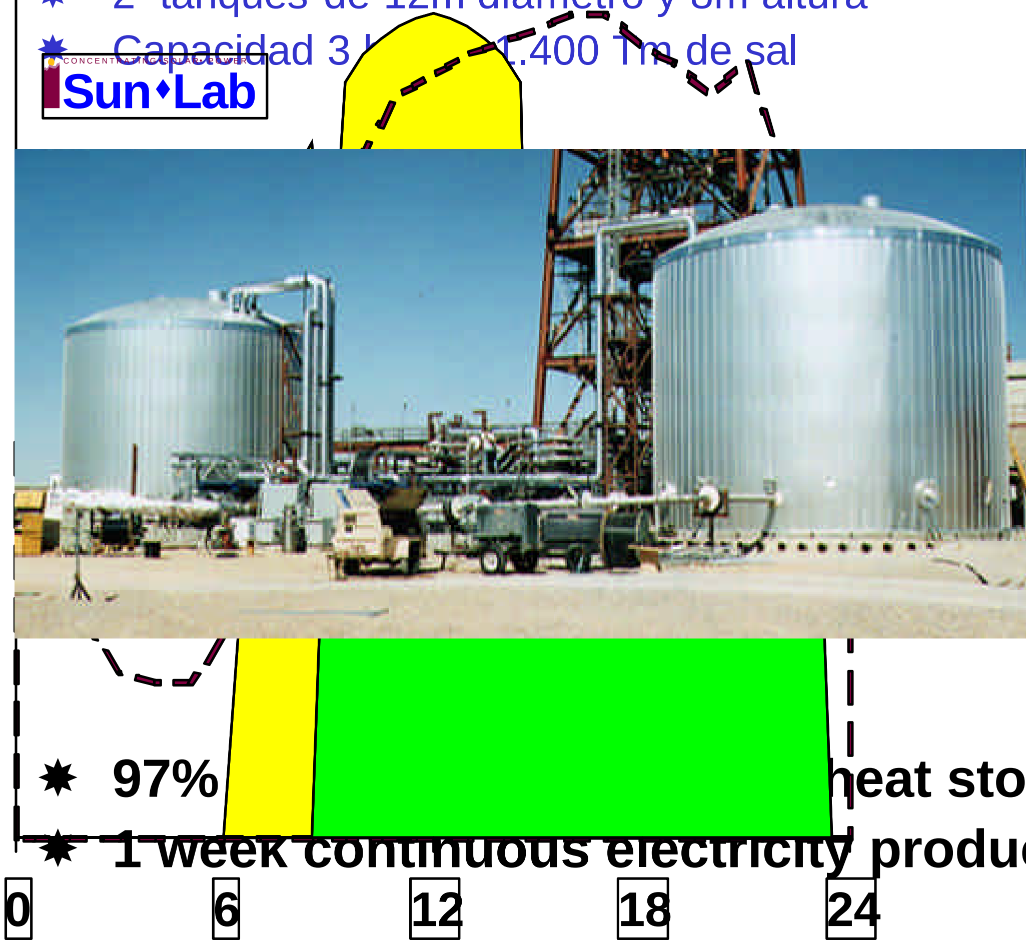
- 42 MW thermal
  - 6,2m high y 5,1m diameter
  - 768 tubes of 2-cm diam.
  - 88% max. thermal eficiency (86% with wind)

Some innovations patented



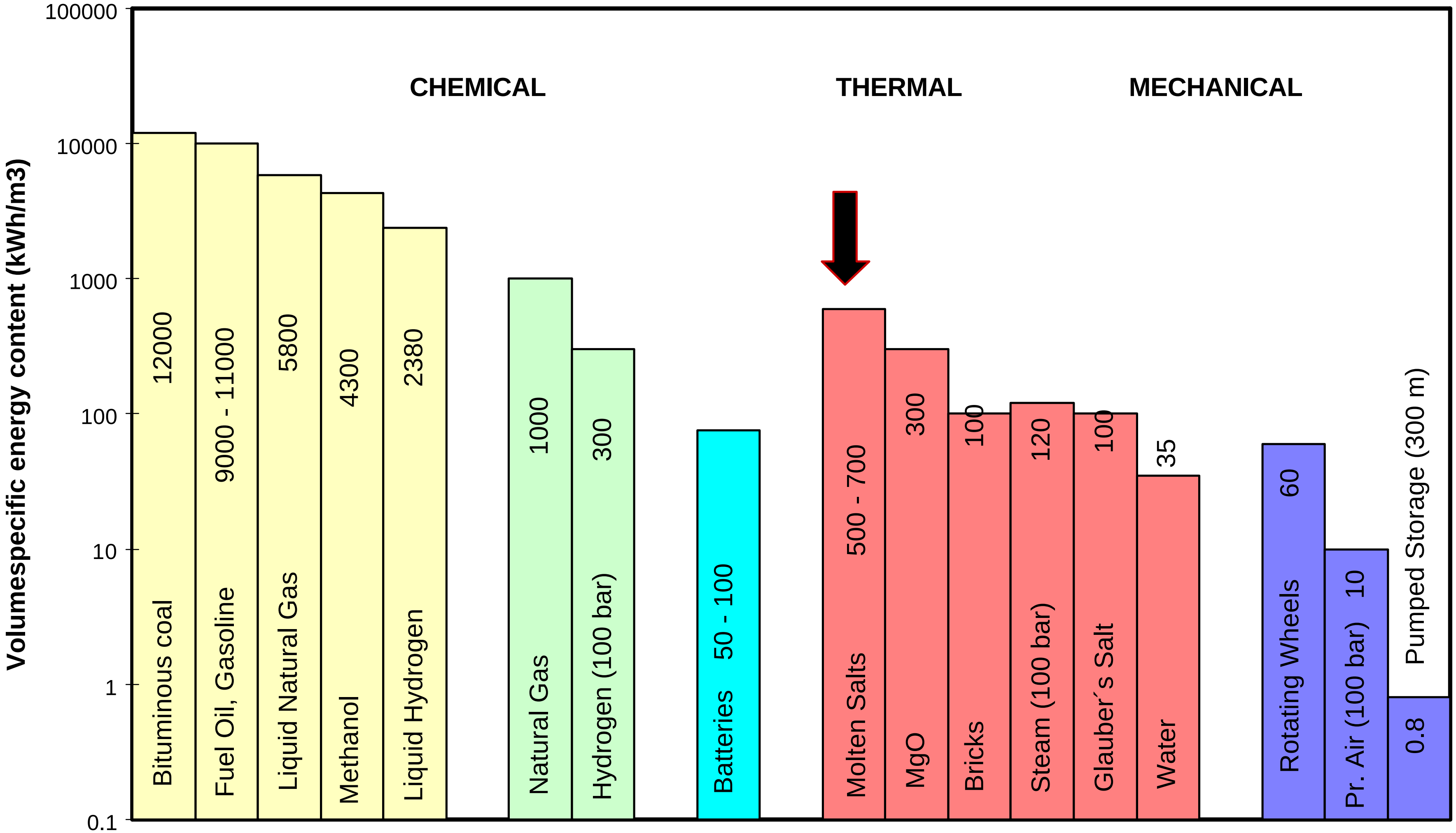
Solar Two: Heat storage

- 2 tanques de 12m diámetro y 8m altura
- Capacidad 3 [illegible] 1.400 Tm de sal



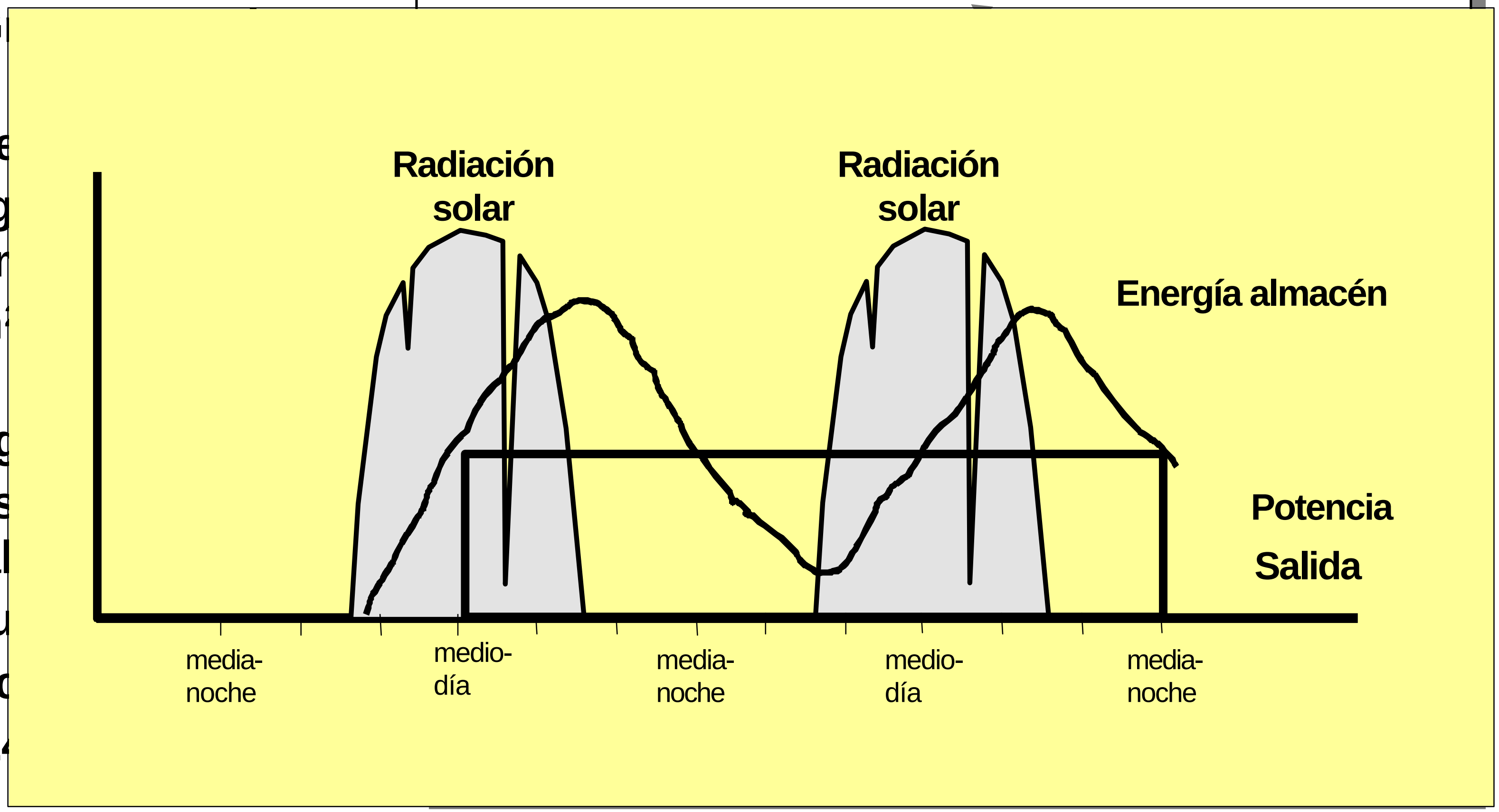
- **97% [illegible] heat storage**
- **1 week continuous electricity production (dispatch)**

Capacidad de almacenamiento térmico



Solar TRES Project

- 17-MW (bruto)
- 84 GWh G
  productio
- 40 MW$_t$ ste
- 120-MWt g
  (8,4x10,5 r
- 263.600 m
  field
- 140 m heig
- 16-hours s
  tons of sal
- 3 solar mu
- 63% capac
- Dispach 2
  (summer)



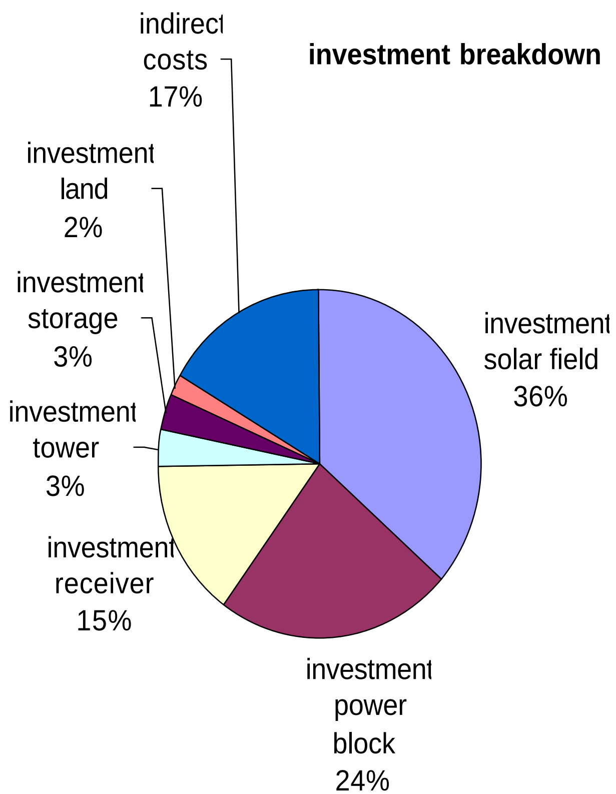
Solar Two ---> Solar Tres

	Solar Two Goal	Actual 7/4/98	Commercial Plant
Mirror Reflectivity	90%	90%	**94%**
Field efficiency	69%	61%	**74%**
Field availability	98%	94%	**99%**
Mirror cleanliness	95%	95%	**95%**
Receiver	87%	88%	**87%**
Storage	99%	99%	**>99%**
Overall Solar Collection	50%	43%	**57%**
Power Generation	34%	34%	**43%**
Parasitics	88%	87%	**93%**
Overall Daily Efficiency	15%	13%	**23%**

Solar Tres ---> "Solar 100"

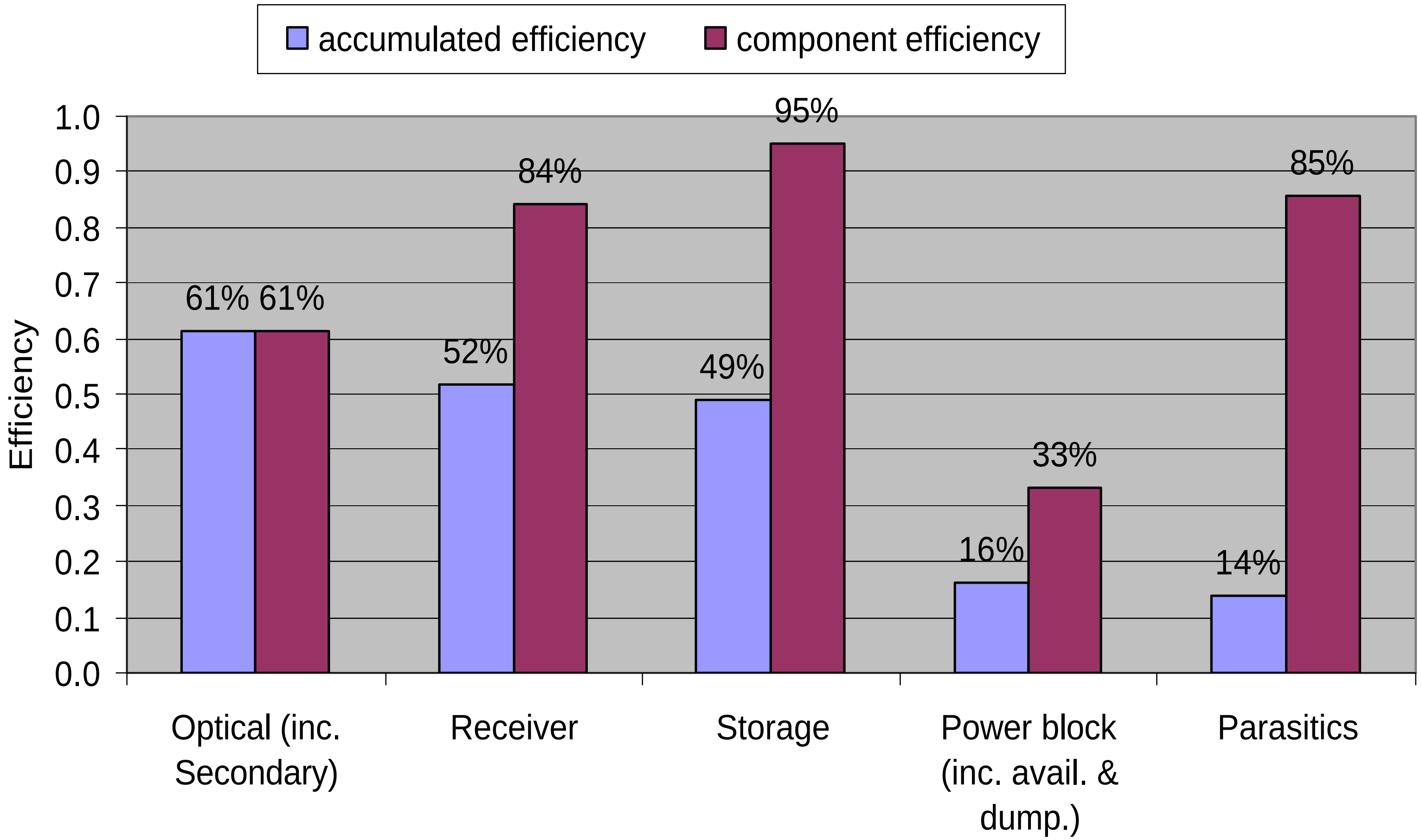
- **Feasibility study** promoted by Eskom and completed in January 2003.
- **100-MW Molten salt** type CRS plant.
- Heliostat and conceptual design have been done with Nexant.
- The site is near Uppington (South Africa´s Northern Cape province), with 2900 kWh/a and moderate winds.
- Financing approval by phases in 2004.

Cost distribution and main figures of the CRS reference plant with molten salt and 3h thermal storage

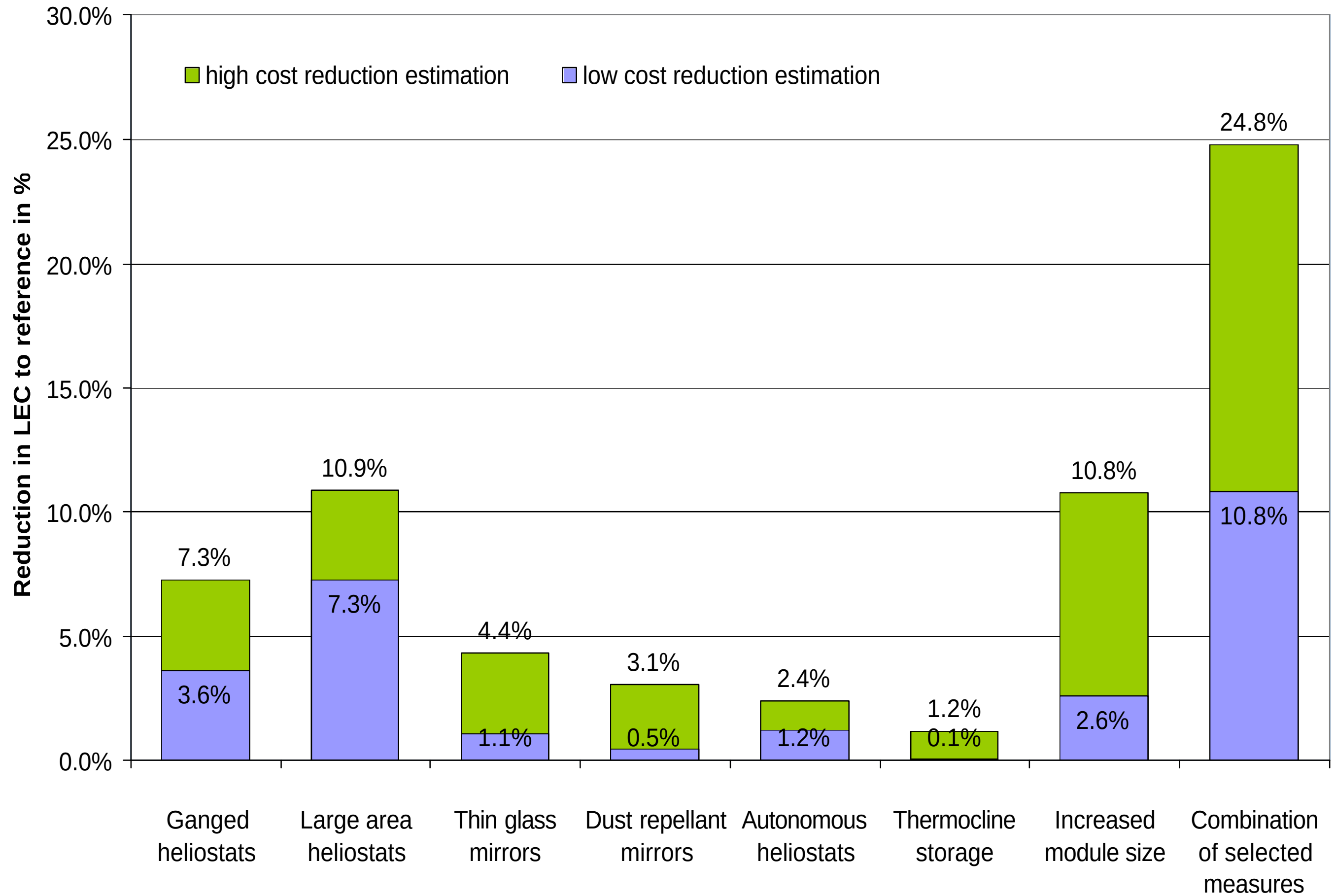


Results		
Specific investment costs	3 473	€/kW$_{el}$
Capacity factor	33.3	%
Fraction of the load demand satisfied by solar	29.2	%
Levelised electricity costs (solar-only)	0.154	€/kWh$_{el}$
Included O&M cost / kWh	0.036	€/kWh$_{el}$

Annual performance of the parabolic trough reference plant with HTF and 3h thermal storage

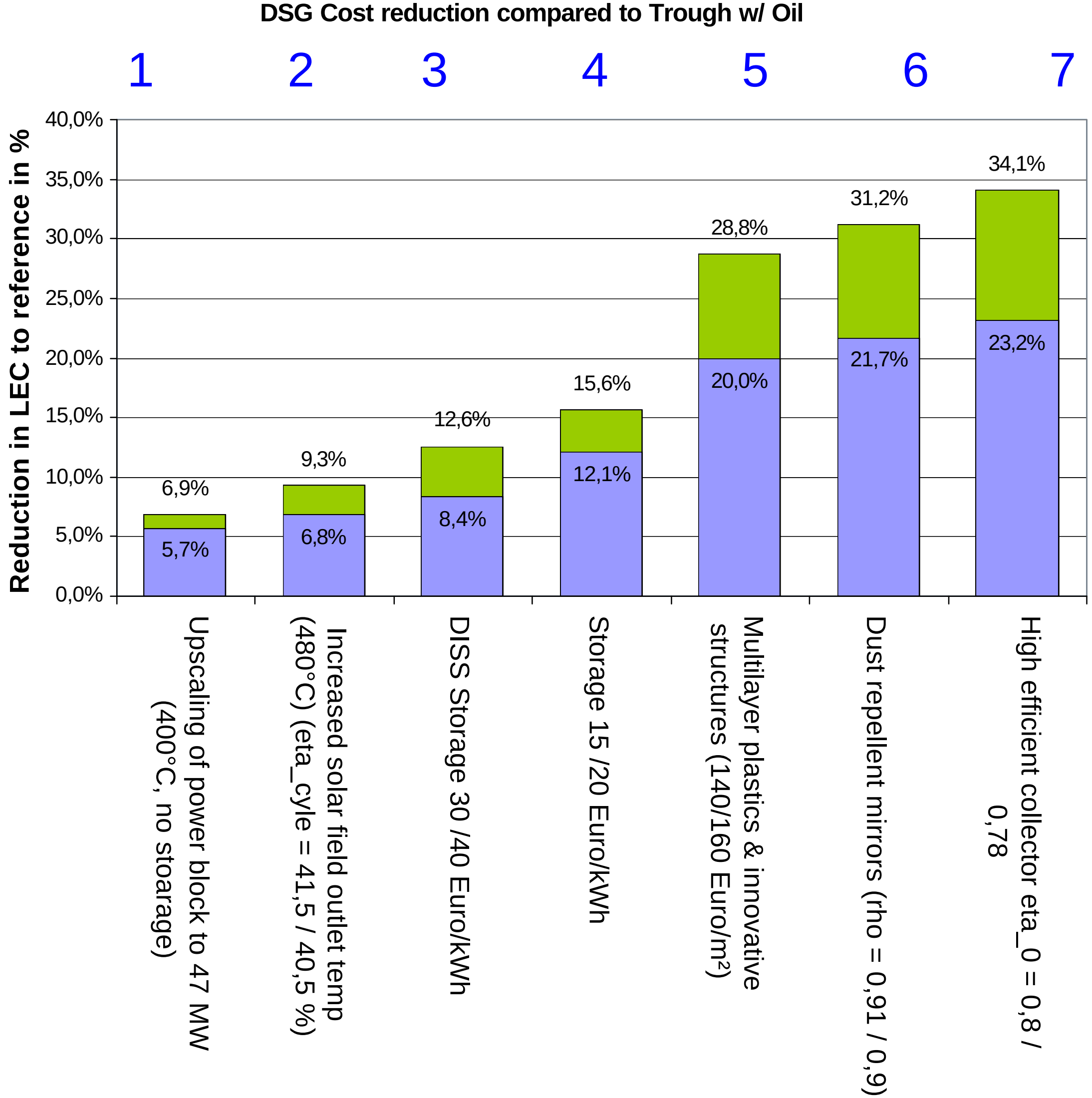


Impact of innovations on LEC for solar-only operation of a CRS with molten salt and 3h thermal storage (full load from 9a.m. – 11p.m.)



Example Direct Steam Generation

1. DSG 400°C no storage 50 MW
2. Increased Temp. 480°C (?$_{cycle}$= 41,5 / 40,5 %)
3. DSG Storage (30 /40 €/kWh)
4. DSG Storage (low cost) (15 / 20 €/kWh)
5. Cheaper Collector Structure (140 / 160 €/m²)
6. Dust repellent mirrors (? = 91% / 0,90%)
7. High efficient collector (?$_{opt}$=78% / 80 %)



How to achieve a cost reduction by a factor of 3 ?

Parabolic Trough (today 50MW) 100%

- Innovations - 35%
- Scaling to larger sizes (400 MW) - 15%
- Volume Production (600 MW/year) - 15%
- **Parabolic Trough in 2020 35%**

? 6 cent/kWh in Southern Europe

? 4,5 cents/kWh in Northern Africa

Findings of the ECOSTAR Study

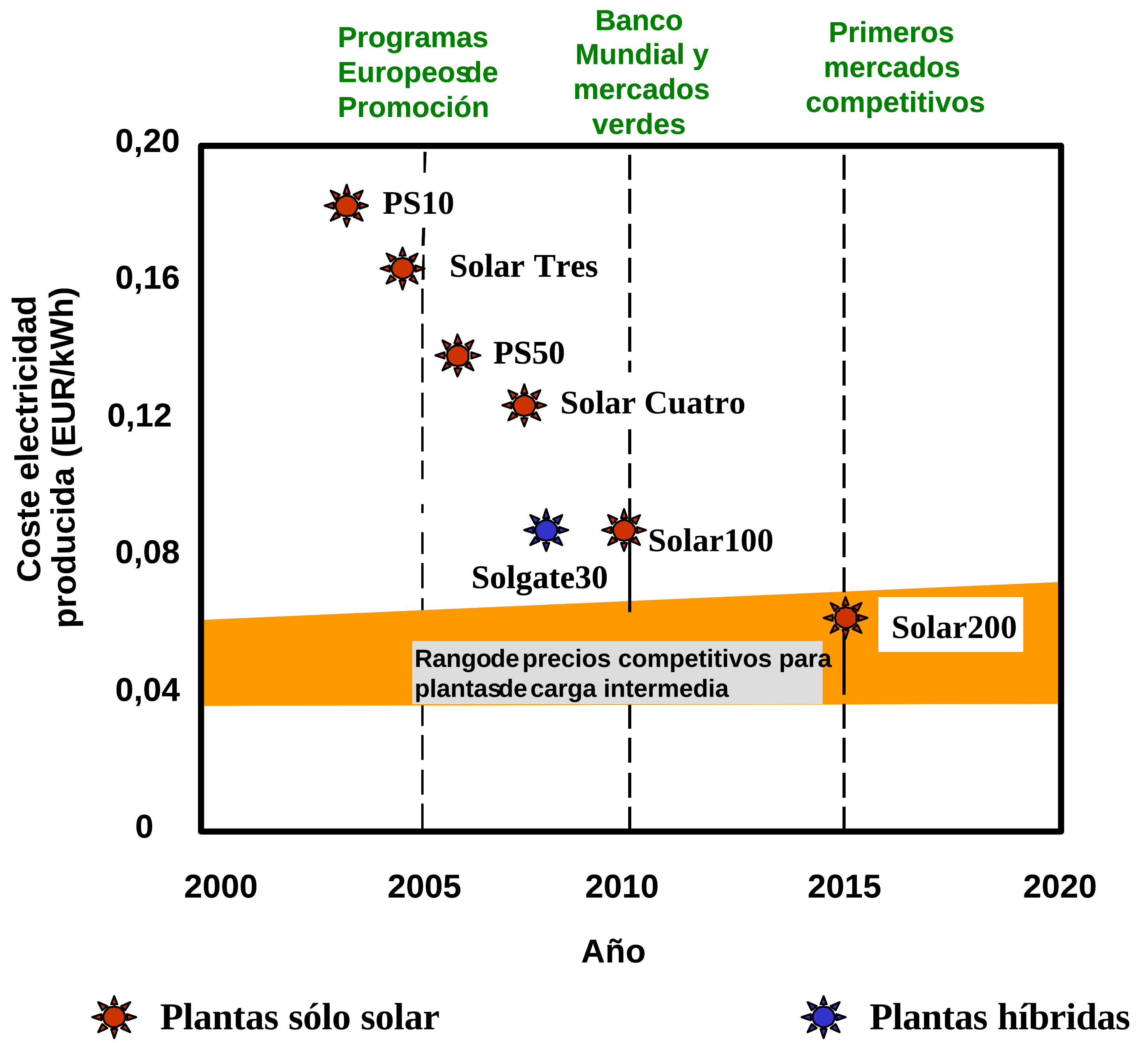
- Further cost driven research is needed to bring the cost to a competitive level
- All presented technologies show the potential to reach this level
- **Short-to-medium term research should focus on modular components like concentrators, receivers etc**.
- **Medium-to-long term research should focus on less modular components like thermal energy storage systems or the integration aspects**
- Competition should be stimulated by giving similar starting conditions to a number of technical options and consortia

Findings of the ECOSTAR Study 2

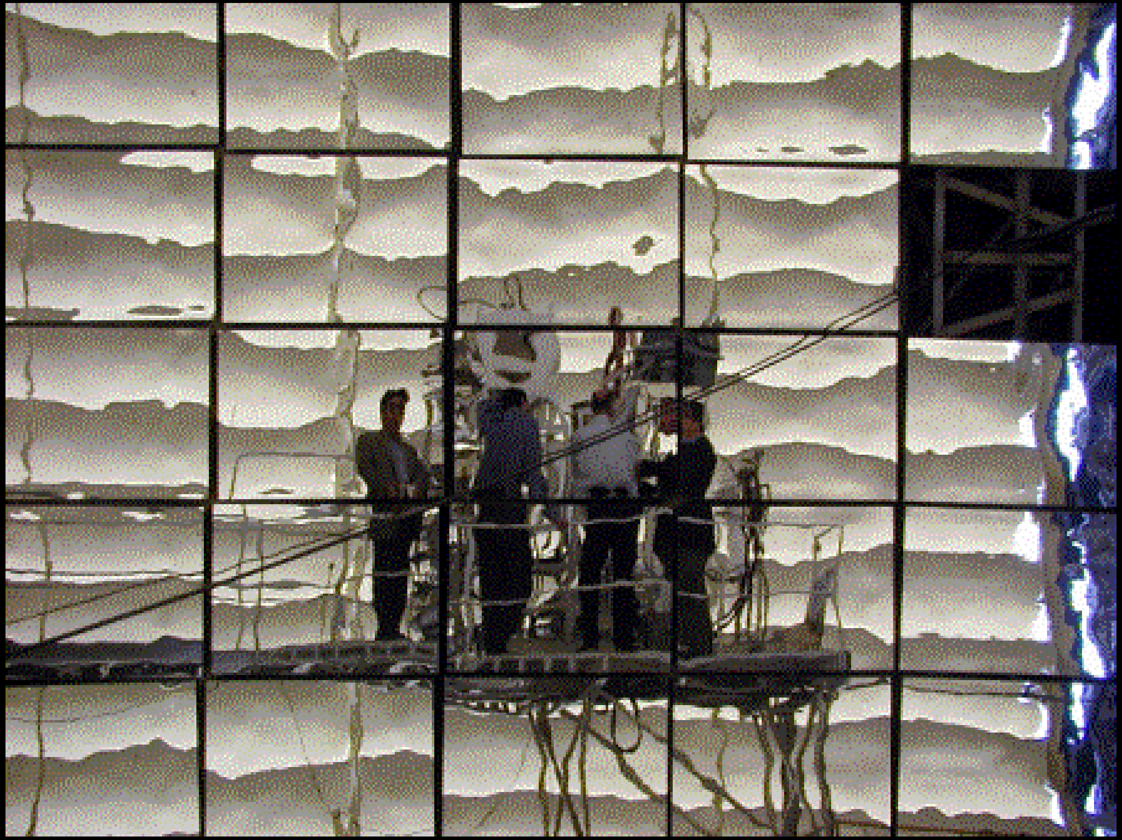
- Further expertise needs to get involved:
  - Large companies from the power sector
  - Specialists in glass, reflectors, light weight structures, drives, outdoor plastic etc.
  - Chemical industry to work on improved HTF or storage media
  - Companies specialized in mass production and logistics (like car manufacturer)
  - Large construction companies capable to design and build storage containers and able to handle and transport hot fluids
  - Technical supervising companies to achieve a high quality control to reduce risks specifically in the scaling process

Findings of the ECOSTAR Study 3

- More countries need incentive schemes similar to the one in Spain, to extend the deployment of the technology.
- The European market should be opened for the import of solar electric from Northern Africa. Higher insolation levels overcompensate the cost for the transport and the deployment of the technology helps to support the political stability in this region
- Hybrid operation of CSP systems is of high benefit for both, the cost of the solar electricity as well as for the stability of the grid. The legal frameworks should be more flexible to allow this option.
- Scaling up CSP to larger power block sizes is an essential step to reduce electricity costs. Incentive schemes should not limit the upper power level to fully exploit the cost reduction potential.


Programas Europeos de Promoción
Banco Mundial y mercados verdes
Primeros mercados competitivos
0,20
0,16
0,12
0,08
0,04
0
Coste electricidad producida (EUR/kWh)
PS10
Solar Tres
PS50
Solar Cuatro
Solar100
Solgate30
Solar200
Rango de precios competitivos para plantas de carga intermedia
2000
2005
2010
2015
2020
Año
Plantas sólo solar
Plantas híbridas

THANKS FOR YOUR ATTENTION !



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