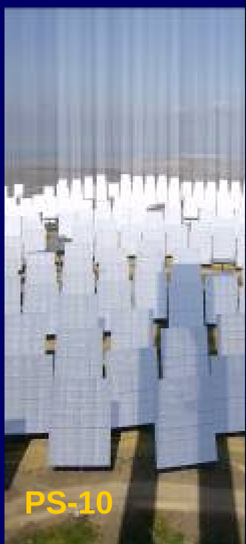
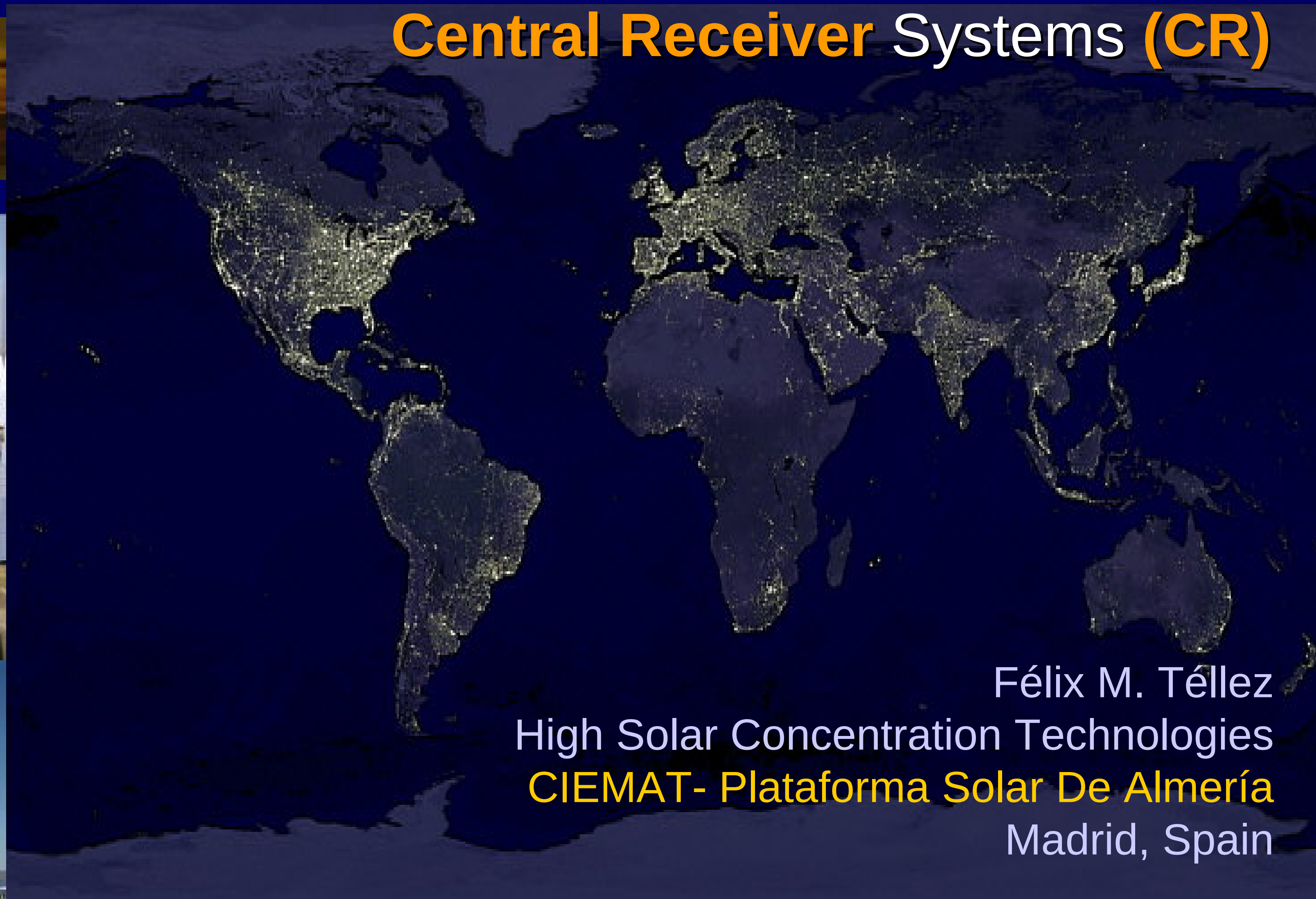
Solar Thermal Electricity (STE) with Central Receiver Systems (CR)



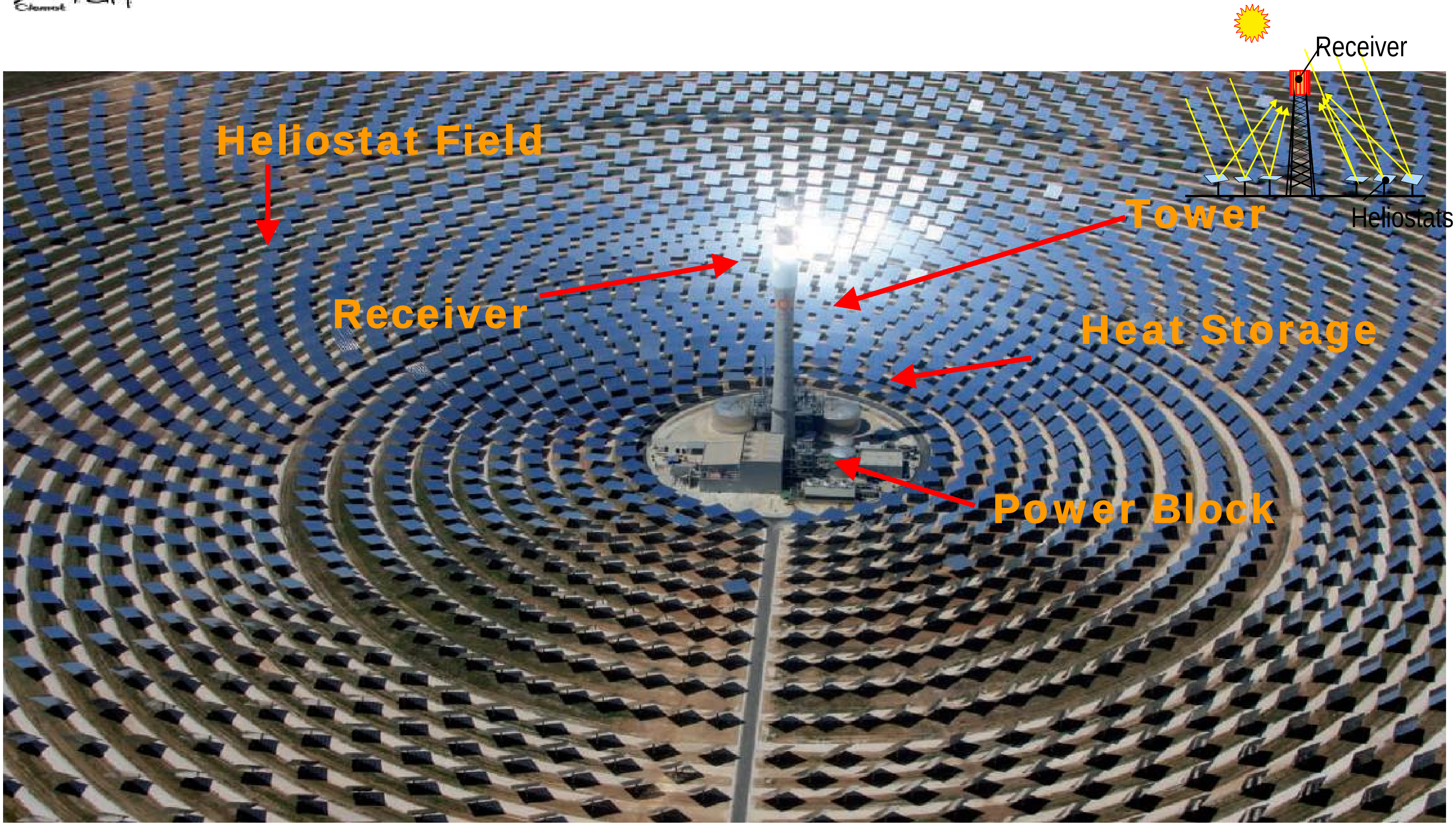


Félix M. Téllez
High Solar Concentration Technologies
CIEMAT- Plataforma Solar De Almería
Madrid, Spain

Contents:

- Overview of STE with Central Receiver Technology
- Development and State of the Art of components
- State of the art of STE-CR plants by heat transfer fluids:
  - Water/Steam
  - Molten Salts
  - Air

Main Components of STE with CR



(some) Key factors of STE-CR

- High Solar Concentration may provide higher overall plant efficiencies (solar fluxes about 100 times larger than in Parabolic Trough technology)
- The Solar Field (consisting of heliostats, each curved, and provided with tracking motors) represents around 30-50% of the necessary investment in equipment.
- The Receiver (combined with its location on the tower) is a key element that requires careful technology solutions to ensure high efficiency, easy operation and high durability.
- The dispatch ability of these systems can be higher than other CSP or STE technologies, (Thermal storage of up to 15 hours has been demonstrated and up to 20 hours are under development)
- Two axes tracking implies:
  - Higher land requirements (e.g. than Parabolic troughs) ~20% ground occupation (=mirror area/total area)
  - Lower requirements on civil works for flattening terrains (up to 3-4% is allowed)
  - Better use of DNI resource (=higher efficiencies) (about a 10% more DNI collection than PT for a same aperture)
  - High investment costs (driving mechanisms)
  - (probably) Higher cost in maintenance (optical and mechanical) (due to have a “distributed” concentrator)
  - …

CR Systems: A little history

1950's: 'Brainstorming' and firts concepts

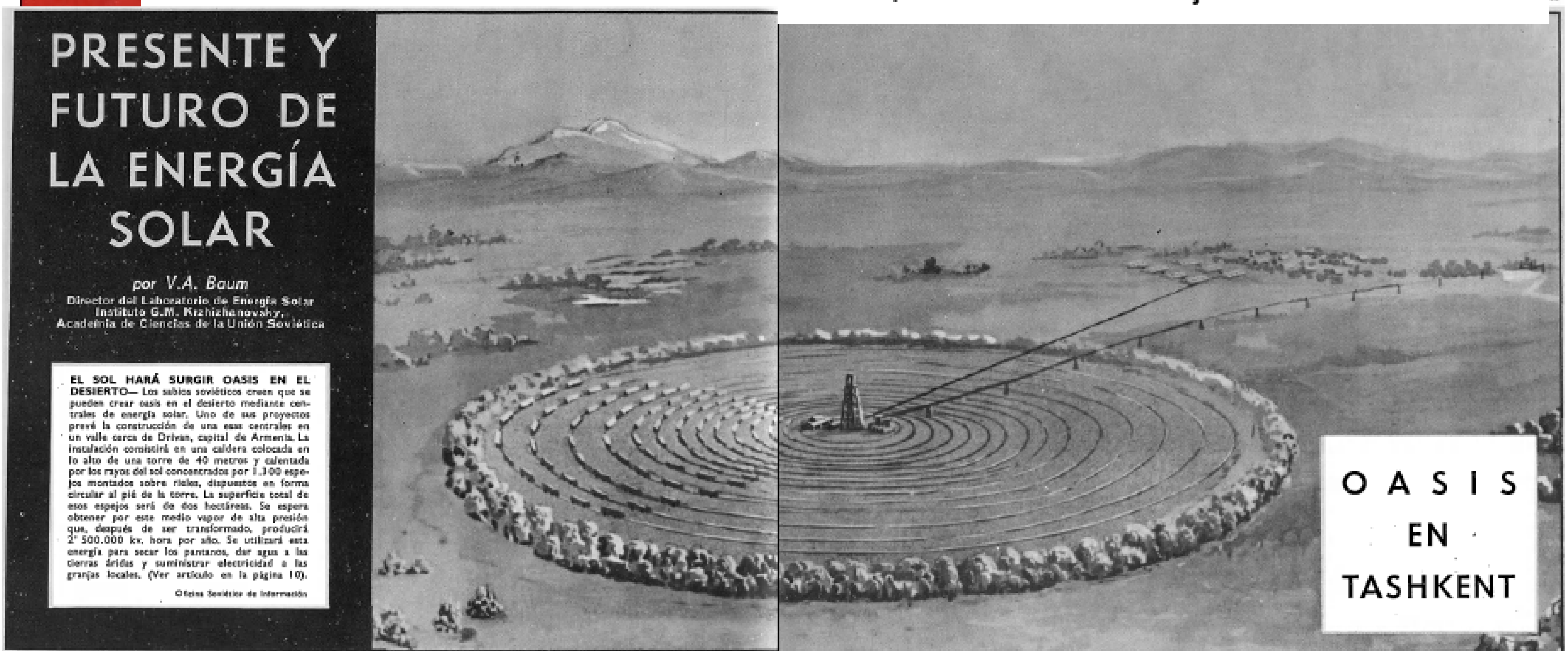
HIGH-POWER SOLAR INSTALLATIONS*

By V. A. BAUM, R. R. APARASI and B. A. GARF

Energeticheskii Institut, Russian Academy of Sciences.

The results of investigations establishing the possibility of erecting economical solar installations in the sunny regions of the U.S.S.R., to produce 11-13 T**/hr of steam, (p = 30 At, t = 400°C), are presented. The optical system of the installation consists of 1,293 mirrors of 3 x 5 m, mounted on carriages which move on rails, positioned around a boiler-shield, on which the solar rays are focused.

SEPTIEMBRE
1958
(Año XI)



PRESENTE Y FUTURO DE LA ENERGÍA SOLAR

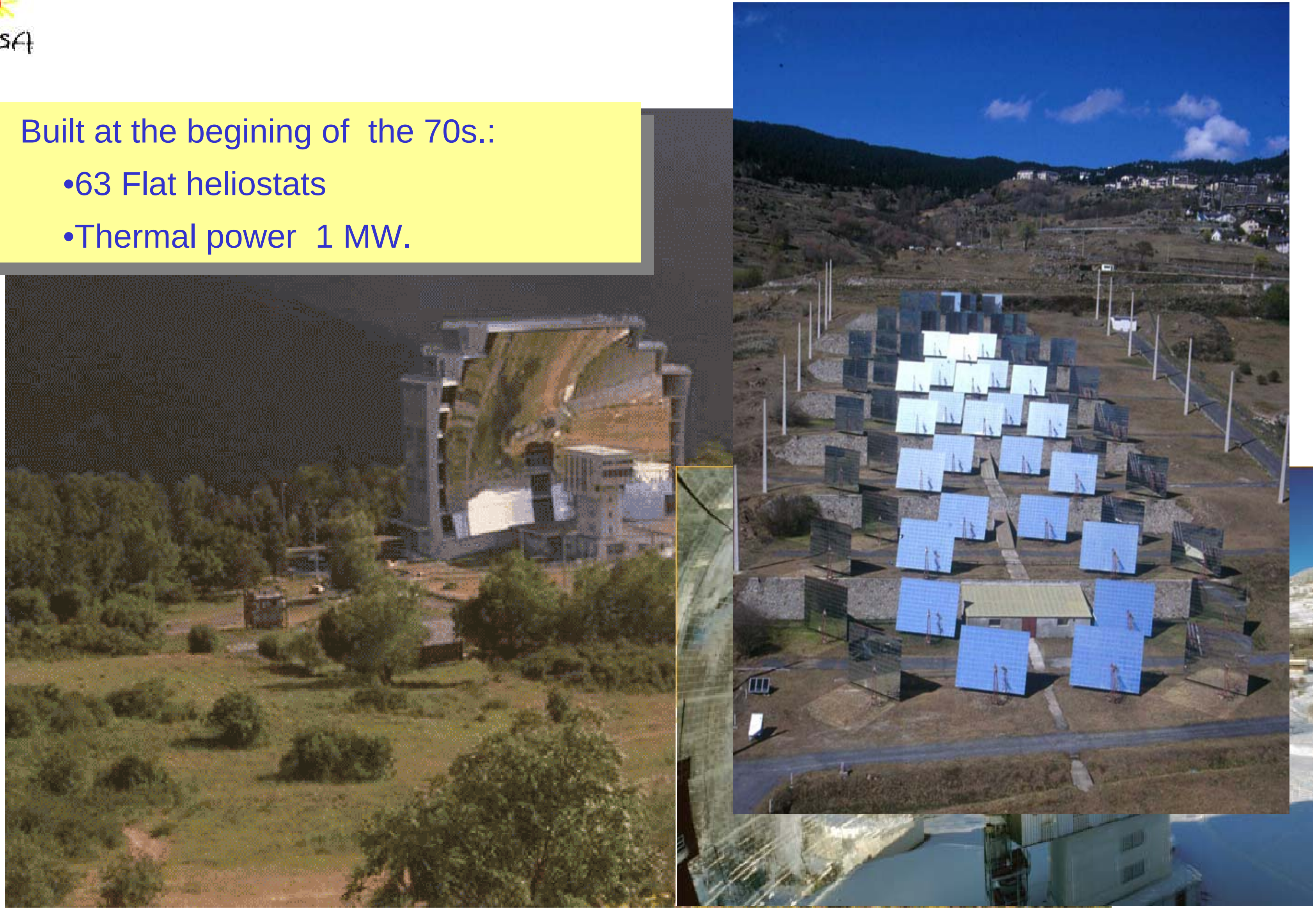
por V.A. Baum

Director del Laboratorio de Energía Solar
Instituto G.M. Krzhizhanovsky,
Academia de Ciencias de la Unión Soviética

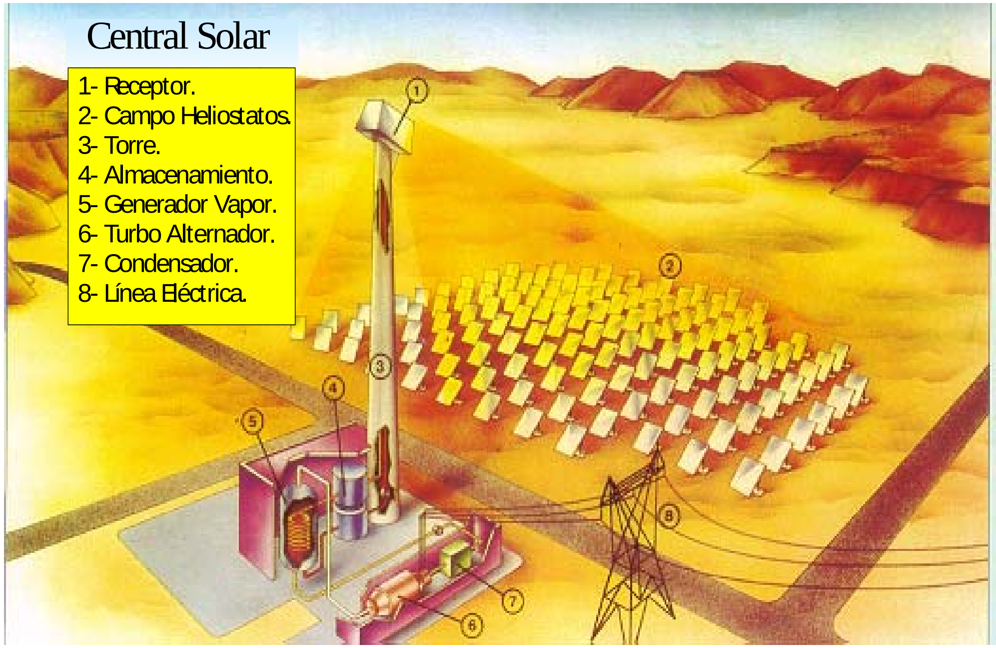
EL SOL HARÁ SURGIR OASIS EN EL DESIERTO— Los sabios soviéticos creen que se pueden crear oasis en el desierto mediante centrales de energía solar. Uno de sus proyectos prevé la construcción de una esas centrales en un valle cerca de Driven, capital de Armenia. La instalación consistirá en una caldera colocada en lo alto de una torre de 40 metros y calentada por los rayos del sol concentrados por 1.300 espejos montados sobre rieles, dispuestos en forma circular al pié de la torre. La superficie total de esos espejos será de dos hectáreas. Se espera obtener por este medio vapor de alta presión que, después de ser transformado, producirá 2' 500.000 kw. hora por año. Se utilizará esta energía para secar los pantanos, dar agua a las tierras áridas y suministrar electricidad a las granjas locales. (Ver artículo en la página 10).

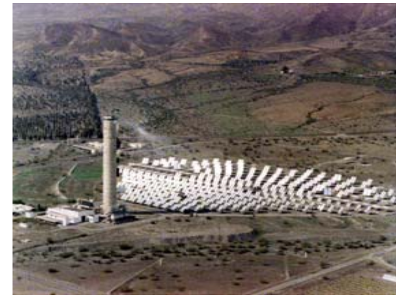
Oficina Soviética de Información

- Built at the begining of the 70s.:
  - •63 Flat heliostats
  - •Thermal power 1 MW.



The 1974 oil crisis prompted the development of a variety of CSP facilities for testing and evaluation of components and demonstration of plant schemes




CESA 1, PSA, Almería, Spain


CRS, PSA, Almería, Spain


SOLAR 1 &2, Barstow, California, USA


ACTF Georgia, USA


NSTTF,Albuquerque, N.M., USA


WEIZMMAN, Rehovot, Israel

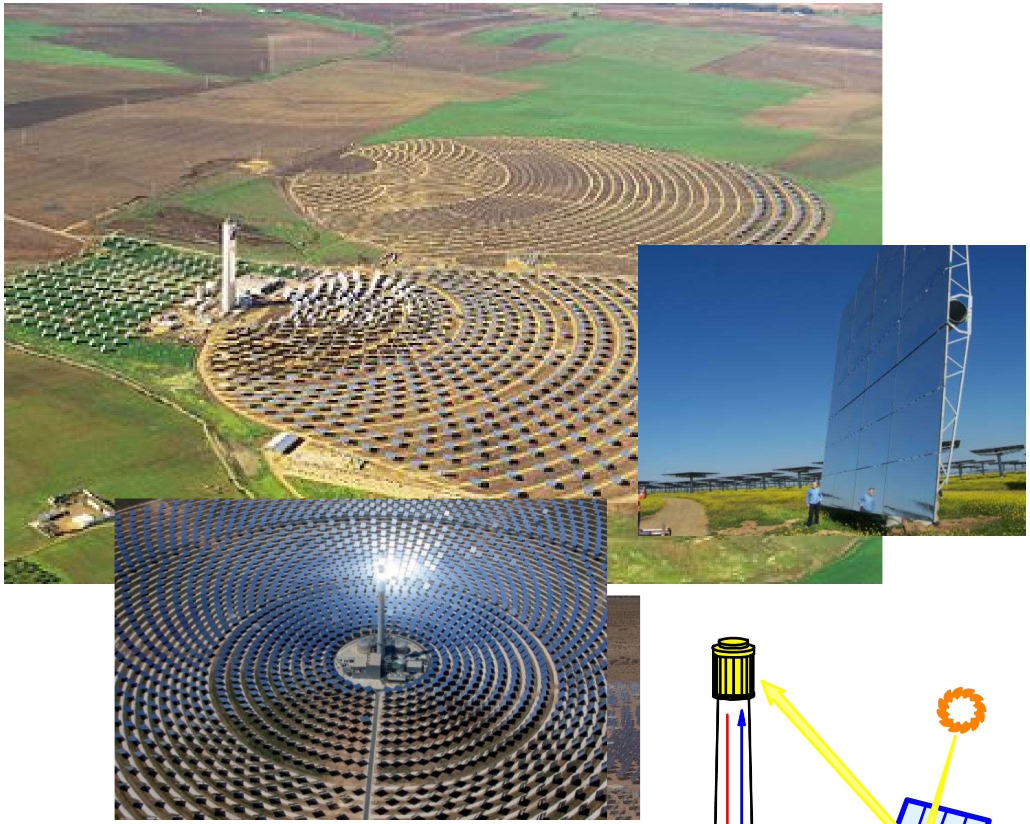

THEMIS, Targassone, France

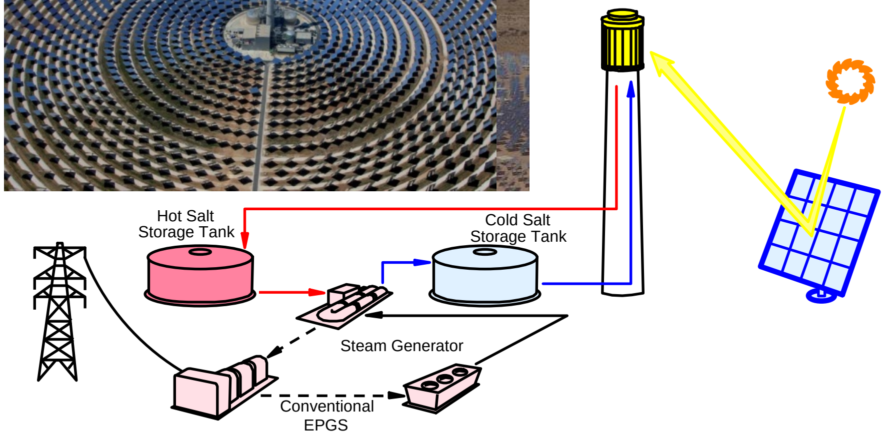

EURELIOS, Adriano, Italy


SUNSHINE, Nio, Japón

STE-CR. Actual Characteristics

- **Two axes tracking** is required. HTF Temperatures between **250ºC- 1100 ºC**. Solar Fluxes of **300-1000 kW/m2**
- **First Commercial Power Plant** (in the world) inaugurated in March **2007**, in Seville (Solucar-**PS10**),
- **Numerous demonstration systems** have **demonstrated** the potential of power towers.
- **Cycles <u>Rankine</u>, Brayton and Combined**
- **Actual Peak overall efficiencies** (solar to electricity**)~ 17-20%**
- **Mean Annual efficiencies** (solar to electricity): **13-16%**
- **Capacity factors up to ~70%** (in Spain and upto 85 % with highest DNI)
- Ongoing projects of plants:
  - ~**100 MW in Spain (50 MWe in operation**: PS10, PS20, Gemasolar**)**
  - …**2,500 MWe in USA**. (eSolar, Brightsource, Rocketdine, Solar Reserve,…) (5 MWe en operación)
  - ~200 MWe in Sudáfrica
  - 50 MWe in MENA
  - China, India, …?





COST AND PERFORMANCE FORECASTS, SL-5641 2003.

STE-CR. Actual Characteristics

- **Learning Curve reactivated** with PS10, PS20, eSolar, Gemasolar, …(reduction of ~15% has been achieved in several components –as heliostats- in the firts 4 years of deployment)
- Although the **maturity** is considered lower than in PT, the **greater potential in efficiency and cost reduction** of CR plants tends to balance the deployment of CR and PT plants.
- **Three preferred technology options**: Water-Steam (saturated, superheated, ...), Molten Salts and Air (atmospheric or presurized).

Project	Country	Power (MW $_e$)	Heat Transfer Fluid	Storage media	Beginning operation
SSPS	Spain	0.5	Liquid Sodium	Sodium	1981
EURELIOS	Italy	1	Steam	Nitrate Salt/Water	1981
SUNSHINE	Japan	1	Steam	Nitrate Salt/Water	1981
Solar One	U.S.A.	10	Steam	Oil/Rock	1982
CESA-1	Spain	1	Steam	Nitrate Salt	1982
MSEE/Cat B	U.S.A.	1	Nitrate Salt	Nitrate Salt	1983
THEMIS	France	2.5	Hitech Salt	Hitech Salt	1984
SPP-5	Russia	5	Steam	Water/Steam	1986
TSA	Spain	1	Air	Ceramic	1993
Solar Two	U.S.A.	10	Nitrate Salt	Nitrate Salt	1996
Consolar	Israel	0.5**	Pressurized Air	Fossil Hybrid	2001
Solgate*	Spain	0.3	Pressurized air	Fossil Hybrid	2002
PS10*	Spain	10	~~Air~~ **Steam**	Ceramic	~~2003~~ **Sept 2006**
Solar Tres*	Spain	15	Nitrate Salt	Nitrate Salt	~~2004~~ **2008**
PS-20*	Spain	**20**	~~Air~~ **Steam**	Ceramic	**2008**

* Projects under development.
** Thermal

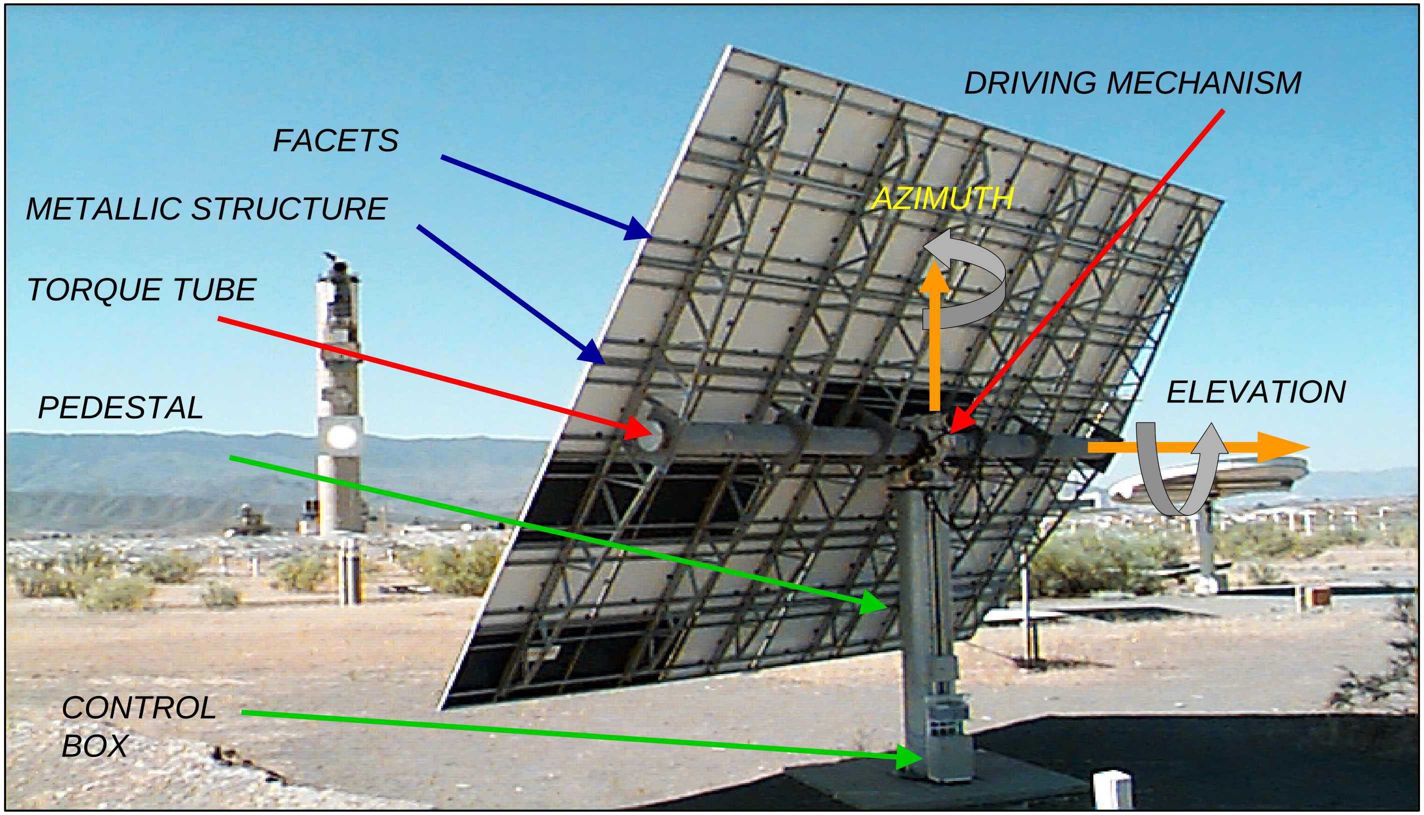
…

CRS: Some key elements.

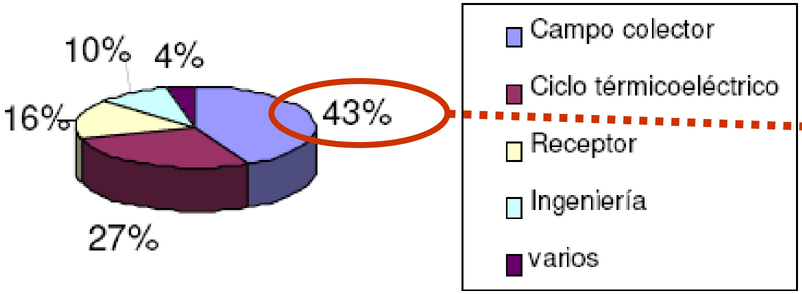
Component's options and new Development

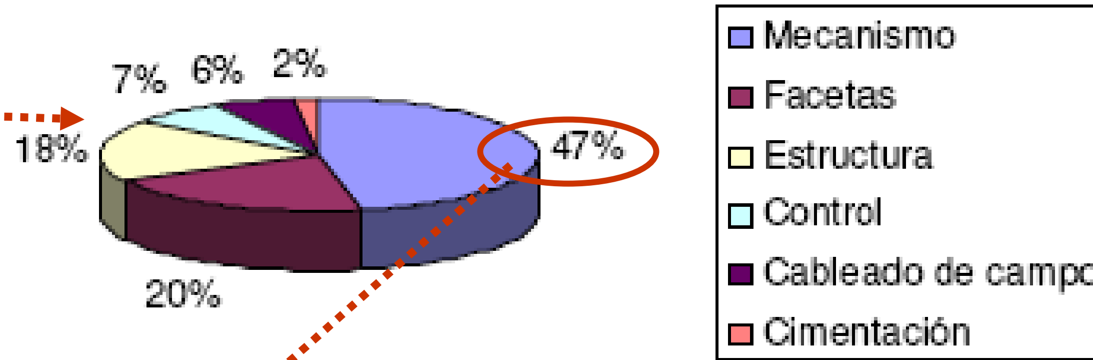
The Heliostat is a key element

A heliostat consists of a large focal **curved** (~spherical) mirror, provided with two axes (and composed of facets, foundation and structure, driving mechanism, controls,…) whose mission is to maintain static the sunlight image on a certain target (typically on the receiver) throughout the day



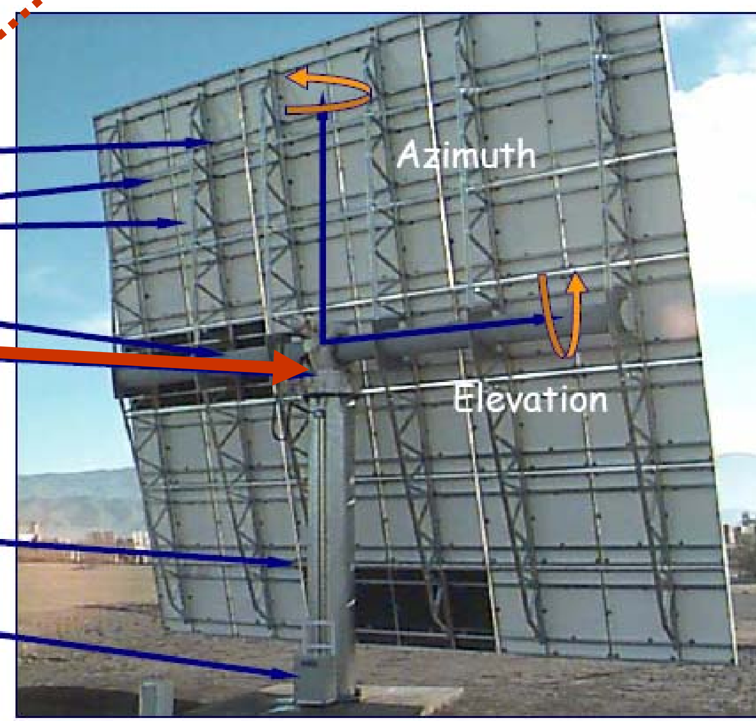
The heliostat is a key element in terms of overall plant investment





MAIN PARTS:

- Facets
- Metal Structure
- Torque Tube
- Drive Mechanism
  - Azimuth
  - Elevation
- Pedestal Tube
- Control



STE with Central Receiver

Heliostats – Developments

In the last three decades a variety of prototypes have been developed and tested. All of them with the main goal of improving performances and/or reducing specific costs (€uros / m2). (R&D explored: increasing size, lightweight structures, alternative reflecting surfaces, different mechanisms, control boxes, wireless communications,...)

SIREC (UE), 16 m^2

Martín-Marietta (EEUU), 40 m^2

Heliostats technology.
Examples of prototypes: Stressed Membrane Concept

SAIC Stretched Membrane Heliostat

SAIC Multi-Facet Stretched Membrane Heliostat

ASM 150 Stretched Membrane Heliostat at PSA

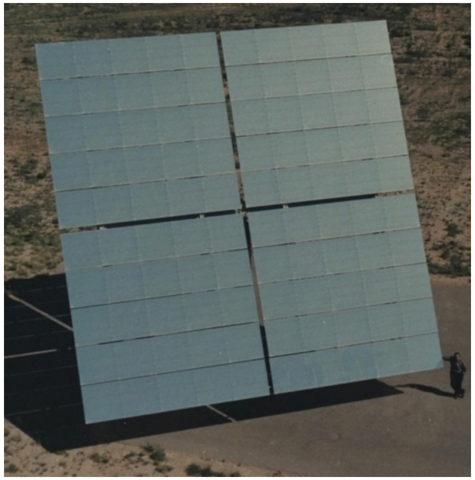
Heliostats technology.
Examples of prototypes: Glass Metal Concept

Decade 1980-1990

CASA (CESA1 40 m²)

ASINEL 65m²

SENER (CESA1 40 m²)



ATS 150

PCHA

Sanlúcar 120 (PS-10 & PS-20)

Space-Cil

H25, H40

SIREC (ETSII)

Latest development:

PCHA: Design PSA. **Autonomous heliostat** based on pre-existing Martin-Marietta. First Autonomous Heliostat Field in the World.

•Sanlúcar 120: Design Solúcar-ABENGOA. Increase size. New local control (PLC)

• H 25: Design PSA. **Flat Heliostat for solar furnace**. Commercial, decentralized drives.

• H40: Design PSA. **Spherical** Heliostat for tower plant. Commercial, decentralized drives.

• Space-Cil: PSA optics & kinematics new concepts, design Solúcar. **Cilindrical Heliostat** for tower plant.

SENER / GEMASOLAR:

-Configuration in “T”

-35 facets, 3mm thick reinforced with galvanized steel **stamping support**, patented by Sener,

- Reflecting surface of 115.7 m2,

-The foundations are made of reinforced concrete,

-Main structure in galvanized steel,

-**Drive mechanism** patented by Sener.

Gemasolar new generation heliostat

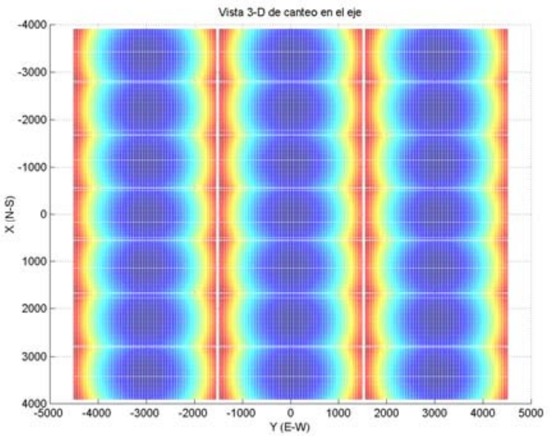
(Lata, J. et al. 2010)

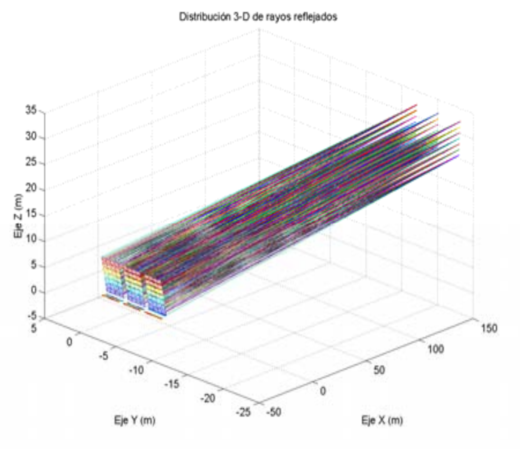
The Optical Quality of the Solar Field (as key) starts with the Optical quality of the heliostat : Curvature / canting of facets and heliostat

Each facet is able to reflect and concentrate solar radiation, so that should be organized geometrically for joint action by all facets of the heliostat → single optical system.

This is known as canting (or alignment of the heliostat’s facets) and provides a single focal

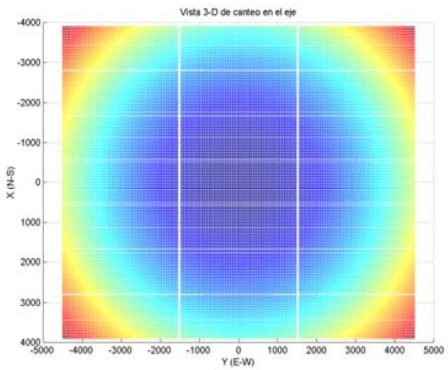
Heliostat Before Canting



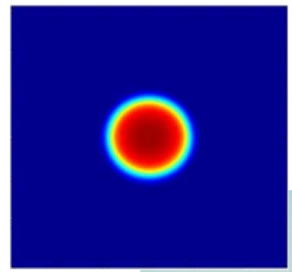


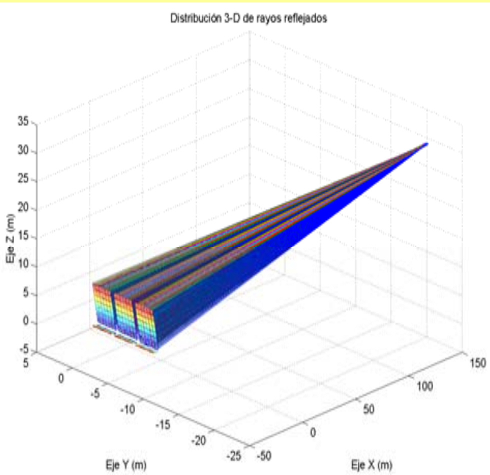
The Optical Quality of the Solar Field (as key) starts with the Optical quality of the heliostat : Curvature / canting of facets and heliostat

Heliostat after Canting

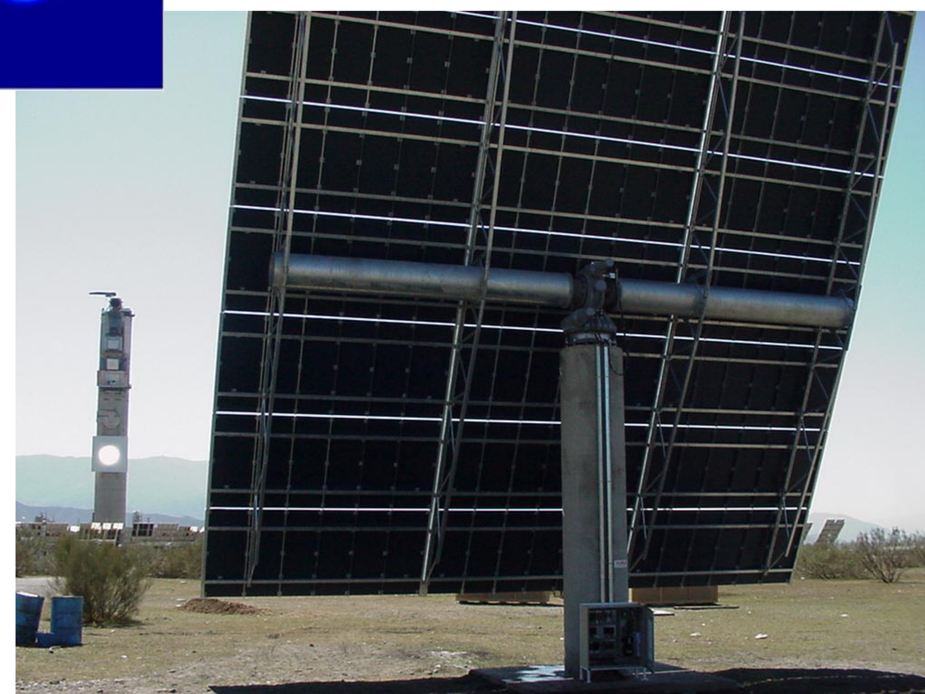


After Canting





Canting purpose to obtain a single focus for all facets of heliostat



This item costs about half the cost of the heliostat. This driving uses two gear motors that guide the mirror surface by two rotations: elevation and azimuth.

Necessary features:

•**Sufficient strength** to withstand the weight, the mobile structure and wind loads, and stiffness to avoid vibration of low frequency.

•Ability to generate **extremely slow movements**.

•High positioning **accuracy and absence of backlash**.

•Possibility of providing a relatively **rapid return to the position of survival**.

•**Resistance to weathering** and atmospheric agents.

•**Ease of maintenance**.

•**Reduced construction and operation costs**.

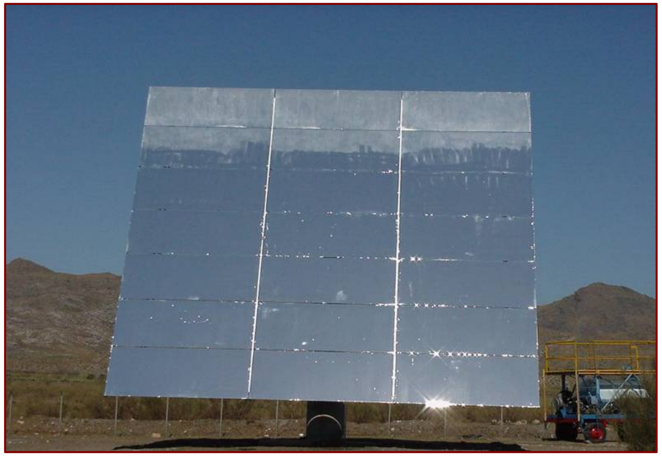
CASA. Ralpe,1980 (40 m^2)

GM-100. Pujol, 1997 (105 m^2)

SENER. PUJOL-SENER, 2005 (115 m^2)

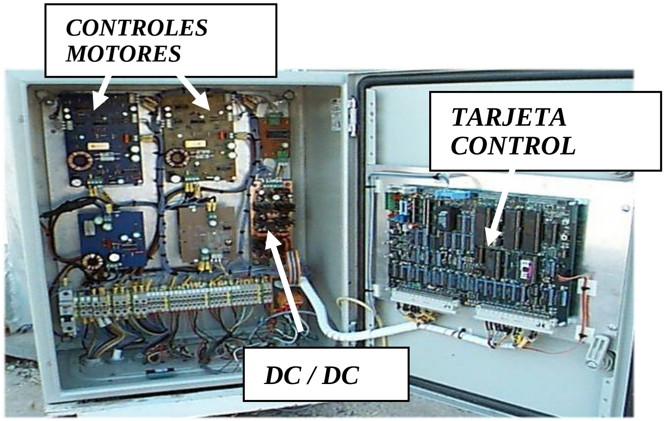
GM-140. Winsmith, 2005 (140 m^2)

Ex. Options for "T" type of heliostats: Mechanical vs Hydraulic drive mechanism (f.i. heliostat Sanlucar, ...)



Heliostats - Components – Control System

Responsible for basic tasks that ensure the proper daily operation of the heliostat, both the point and in emergency situations. Typically we have **two levels of control**: **a) Central Control** – to stablish setpoints and strategies for heliostat operation, **b) Distributed or Local Control** (to translate setpoints to the driving mechanism, ...)



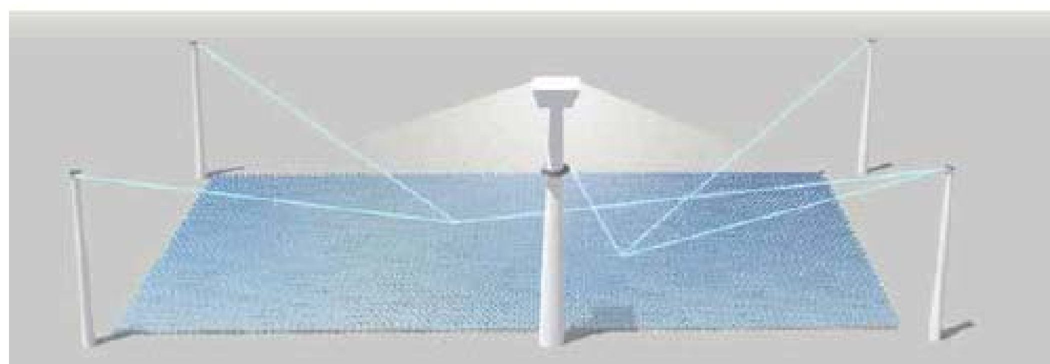
Typical Local Control Tasks:

- *Solar vector calculus,*
- *Control of drive mechanisms,*
- *Calculation and pointing of heliostat mirror surface*
- *Managing of communications with the central control*
- *Auto-diagnosis of errors and faults,*
- *Self-protection in an emergency.*

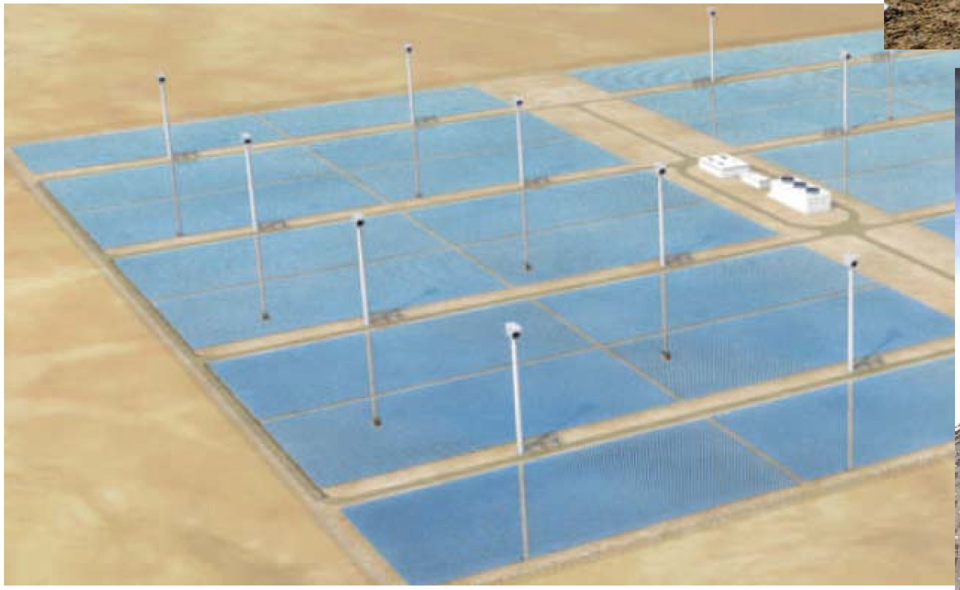
Heliostats

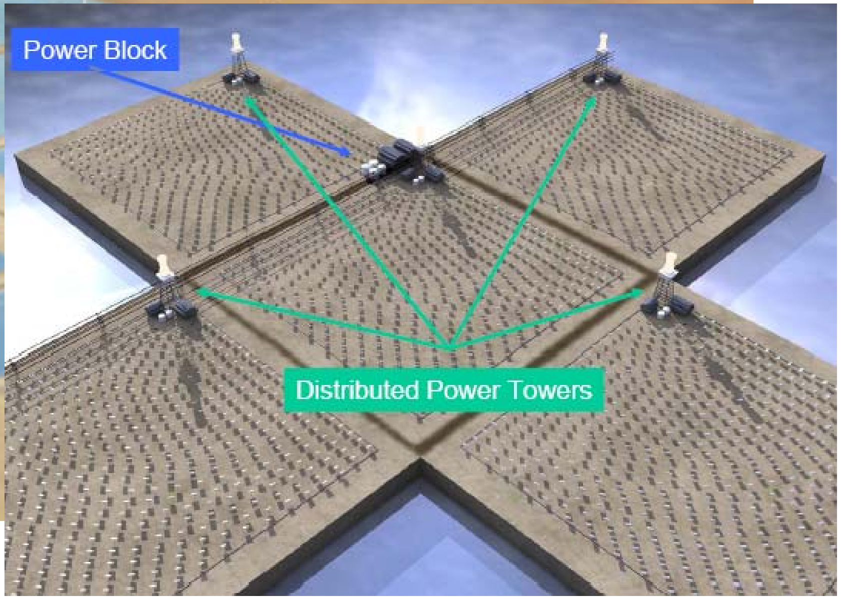
- Historical wisdom of “larger is better” is being challenged
  - 1.14 m² eSolar heliostat -- 24000 in California
  - 7.2 m² Brightsource heliostat – 1640 in Israel
  - 10 m² concrete prototype by SAIC
  - 8.5 m² ganged prototype by Tokyo Tech →
  - Production economies and availability of drives

- 10 to 100 times more heliostats for the same MW
  - Aiming calibration and maintenance are potential issues
    - eSolar automated calibration method



Emerging concepts: More Modularity -> small Heliostat + multitower Systems





Heliostats

- Large heliostats are still in vogue
  - 1880 X 120 m^2 heliostats at PS10/20 (Abengoa)
  - 2650 X 116 m^2 heliostats at Gemasolar
  - 100 X 100 m^2 heliostats in China (Himin)
  - R&D on low-cost drives (Siemens)
  - Mass production of Az drive is needed (Sandia)
    - ~\$44/m^2 given 2500/yr, \$22/m^2 given 50000/yr
- Flat-glass mirrors are relatively inexpensive but are they durable?
  - 4mm mirrors survived 4.5 cm hailstones at 290 km/hr velocity (CSIR)

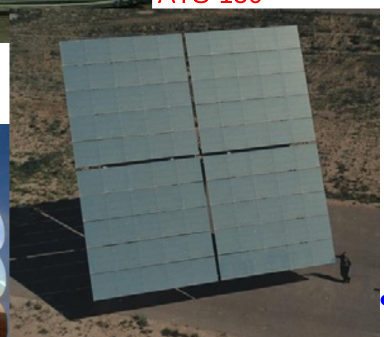
Siemens combo az/el drive

CRS. Actual status of heliostat development

ASM-150

GM-100

ATS-150



SAIC-170

SANLUCAR 120

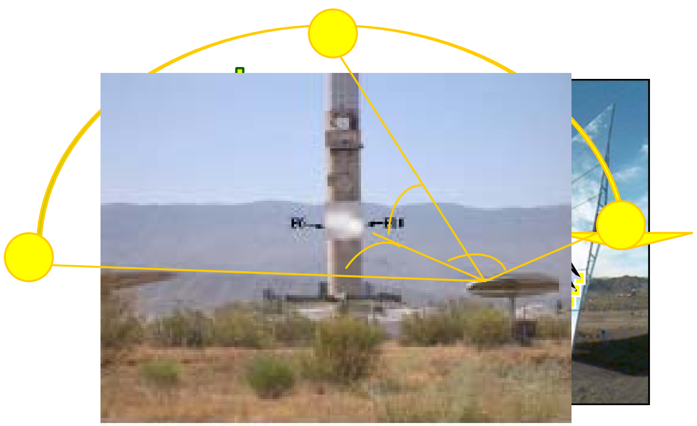
- **Heliostat:** Actual developments have shown an excellent performance with a trend to reduce cost by opposite ways:
  - Larger sizes (from 90 to 150 m2) to attain lower specific costs in the driving mechanism (total investment per square meter of aperture, installed)
  - Smaller sizes (1 to 20 m2) to reduce the requirements on the driving mechanisms, increasing the land occupation and allowing schemes of ganged tracking
- Actual reference may be the Abengoa's and/or the Sener's heliostats (in operation in PS10, PS20 and GEMASOLAR): Sizes ~ 120 m2
  - Prices ~160-170 €/m2 (installed)
- Optical qualities of 2.5 mrad are easily attained and are enough for the first plants.
- Durability of about 20 years has been proved in facilities like PSA
- New Developments are focused in reducing costs in driving mechanism and lighter structures, reducing the cabling requirements by autonomous heliostat, reducing O&M costs, etc.

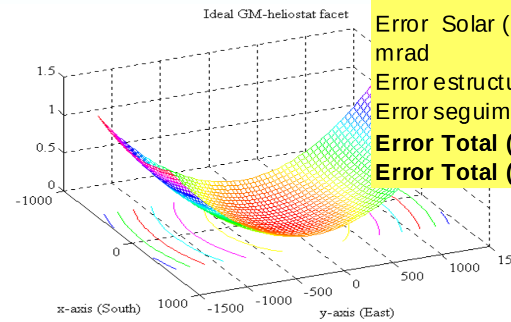
The optical quality is an issue: The combination of imperfections (mirrors, canting, structure, tracking, …) lead to a loss of efficiency (“degraded sun”). An error convolution may be used to quantify the quality.

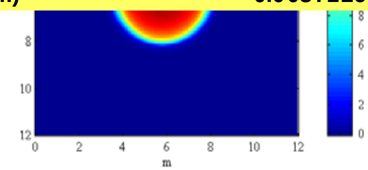
Imperfections

Surface Error

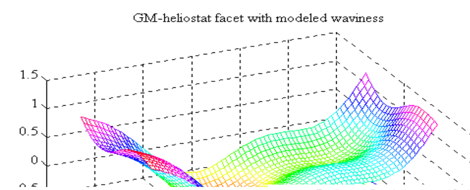
Angulo solar (teta_s), [mrad]	**0.009599333 radianes**
Error Solar (68.3% sign.), mrad	0.0028 **radianes**
Error estructura	0.001979899 **radianes**
Error seguimiento solar	0.002828427 **radianes**
Error Total (68.3% sign.)	**0.004445222 radianes**
Error Total (95% sign.)	**0.008712635 radianes**

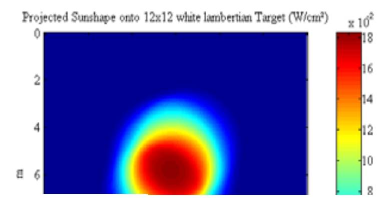




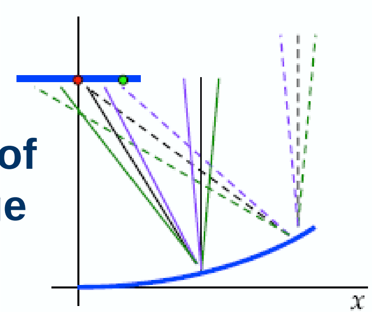


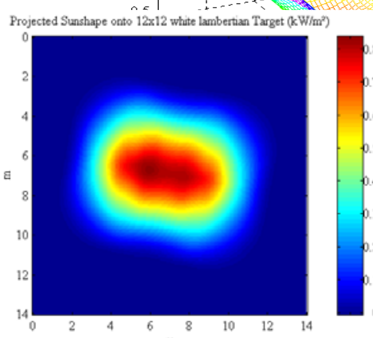
Spherical curvature, no waviness



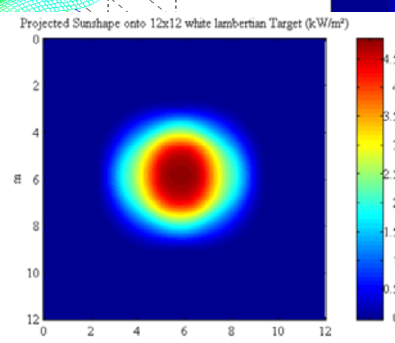


Variability of Focal Image

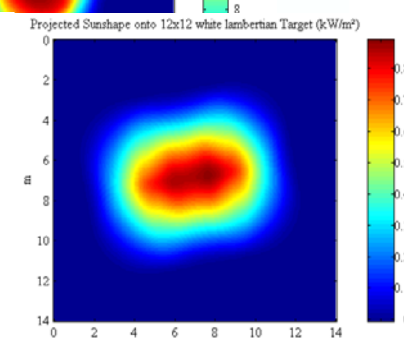




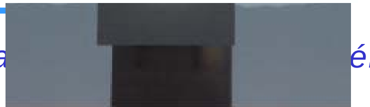
Summer solstice, 7:30 a.m.



Summer Solstice, solar noon



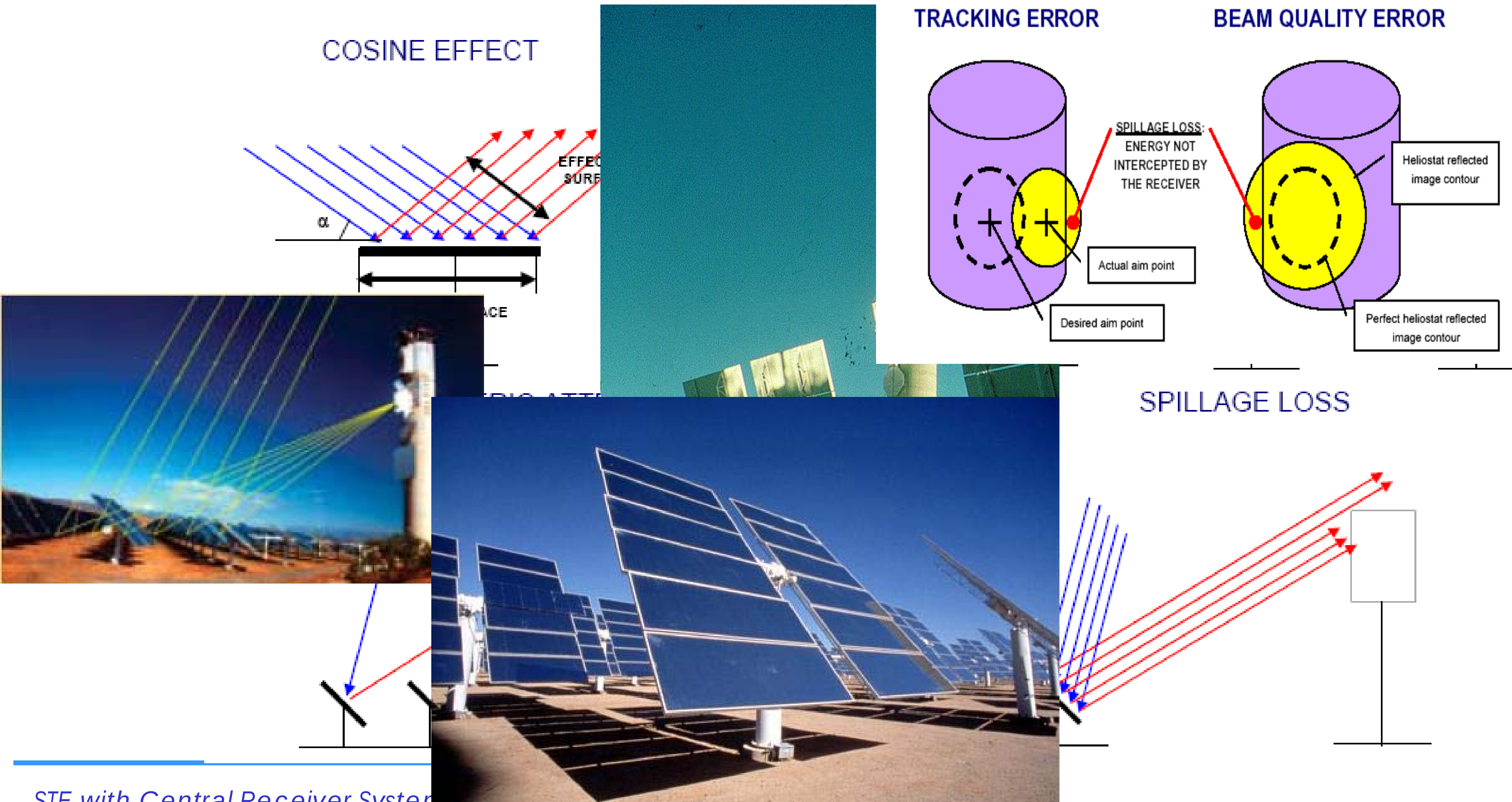
Summer Solstice, 7:30 p.m.



Besides, the loss of efficiency of each heliostat, the solar field may be designed (choosing heliostat distribution, tower heigh, receiver size, …) to obtain the optimum compromise of **efficiency** and costs.

$$\eta_{plant} = \eta_{solar\_field} * \eta_{receiver} * \eta_{power\_block} = P_{electricity} / P_{solar\_incident}$$

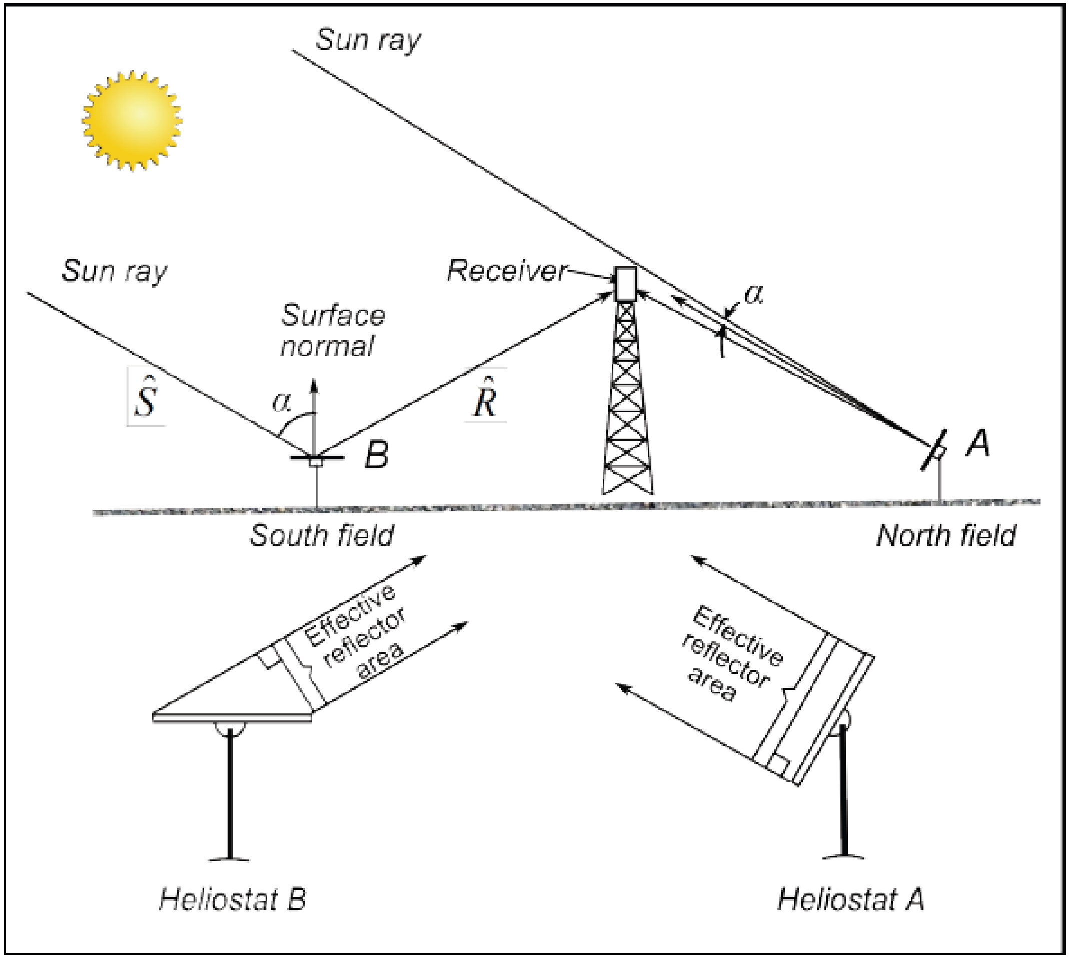
OPTIMIZATION Process I: Optical performance



Besides, the loss of efficiency of each heliostat, the solar field may be designed (choosing heliostat distribution, tower heigh, receiver size, …) to obtain the optimum compromise of **efficiency** and costs.

Cosine Factor

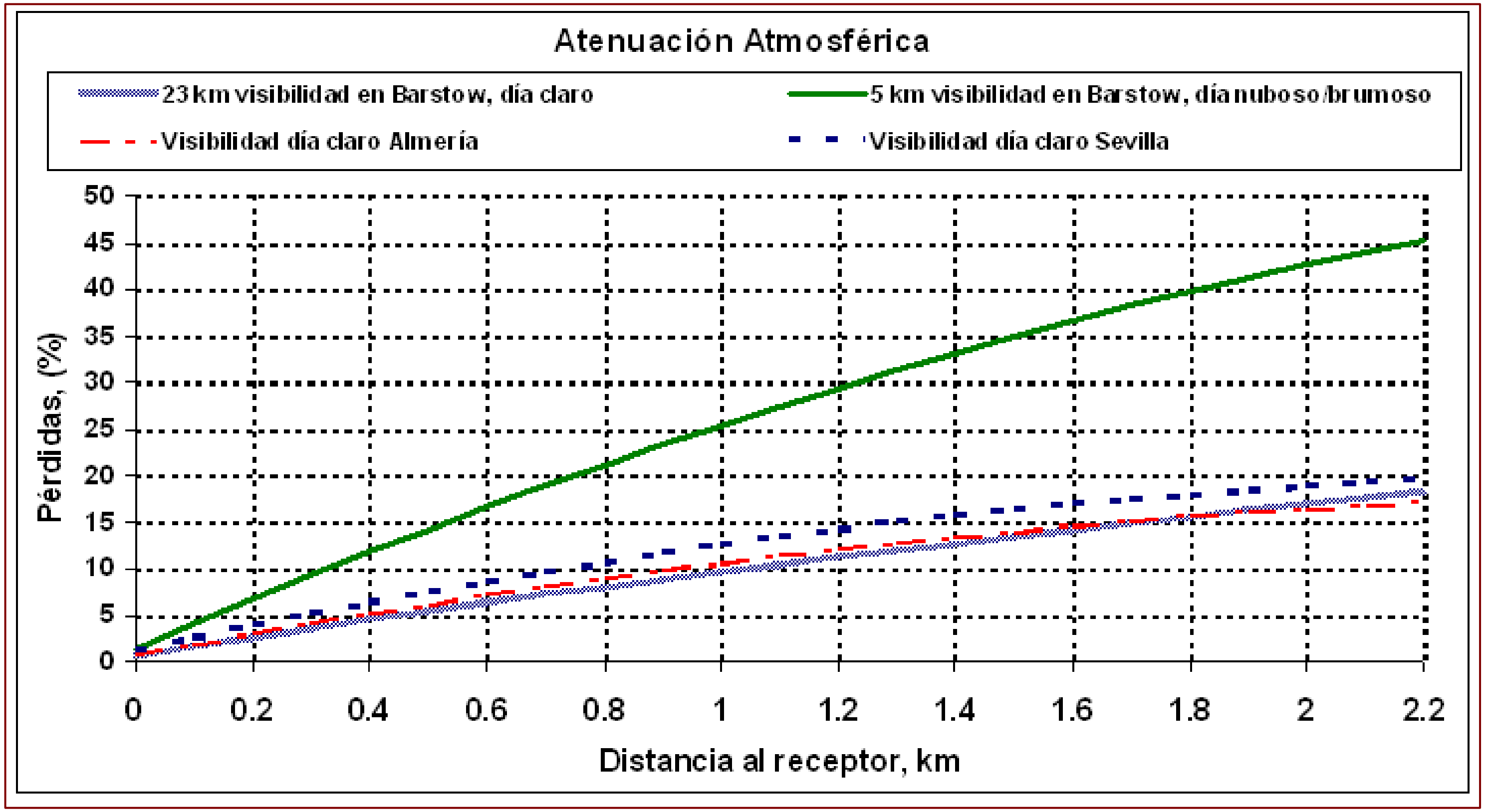
- The cosine factor is one of the most important factors for optimizing the Solar Field optical efficiency.
- Due to the cosine factor, the effective **reflection area is reduced.**
- The cosine factor depends on the sun position and the position of the heliostat in the field respect to receiver (including tower height).
- Typically an annual estimation of the cosine factor is used for solar field design



Besides, the loss of efficiency of each heliostat, the solar field may be designed (choosing heliostat distribution, tower heigh, receiver size, …) to obtain the optimum compromise of **efficiency** and costs.

Atmospheric attenuation

In the case of having a very large solar field apertures, many design factors suggest very tall tower heights and large heliostat field far from the tower. In these cases, ATMOSPHERIC ATTENUATION may be a significant efficiency limitation for heliostat fields having a single tower.

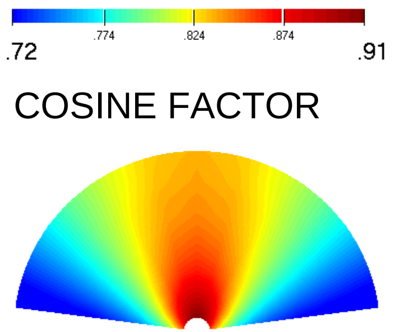


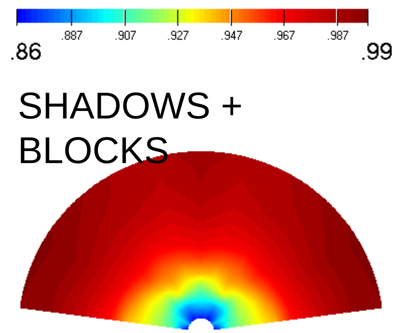
Solar field Maintenance is required to maintain high levels of performance (e.g. in reflectivity by mirror washing, etc.)

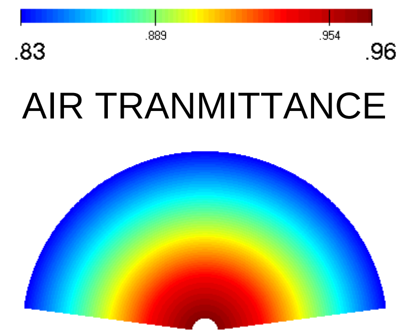
- Required demineralized water of about 0.2 liters/kWh
- Typical frequencies of washing are 2-3 weeks

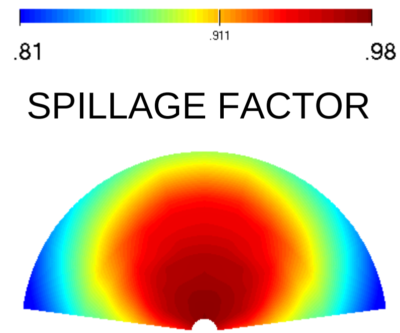
Solar field design is aimed to choose «optimal» coordinates of heliostats respect to the tower (+heliostat characteristics, thermal power requirements on receiver + …)

$$\eta_{plant} = \eta_{solar\_field} * \eta_{receiver} * \eta_{power\_block} = p_{electricity} / p_{solar\_incident}$$









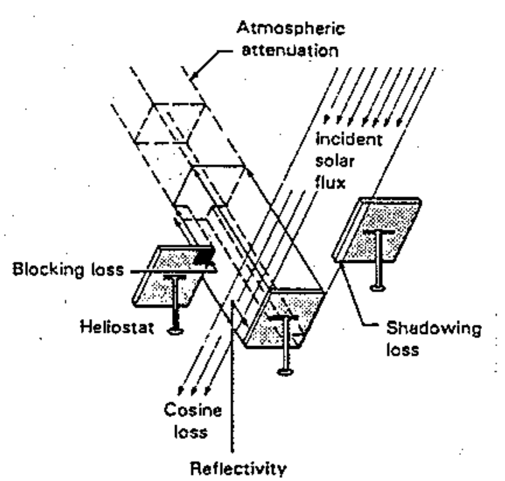
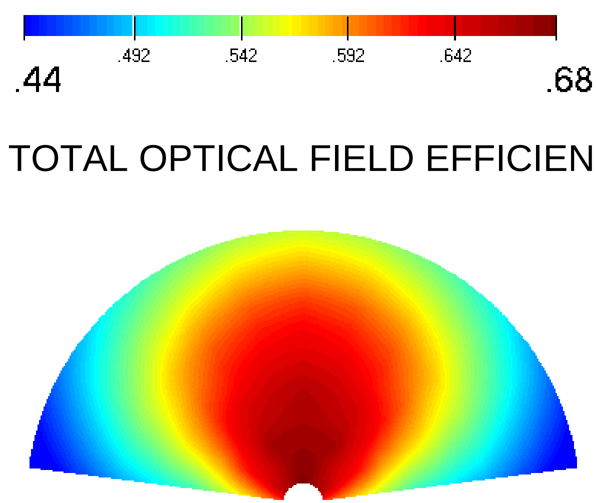
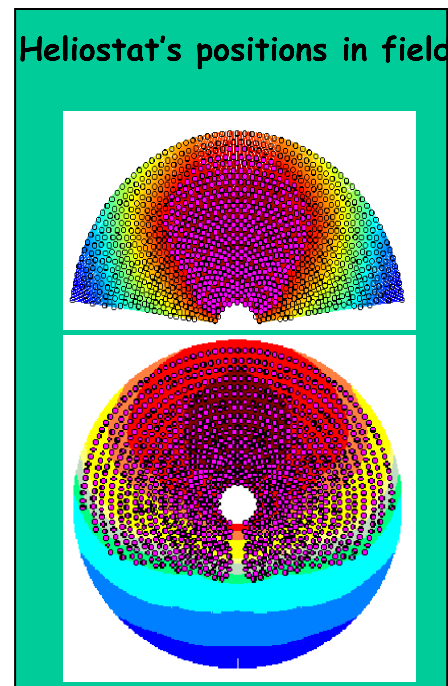


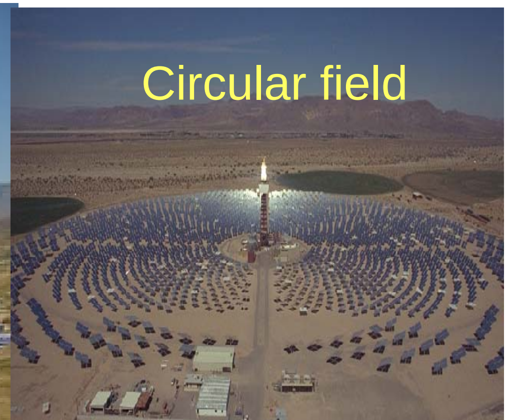
Figure -3 Collector Field Optical Loss Processes

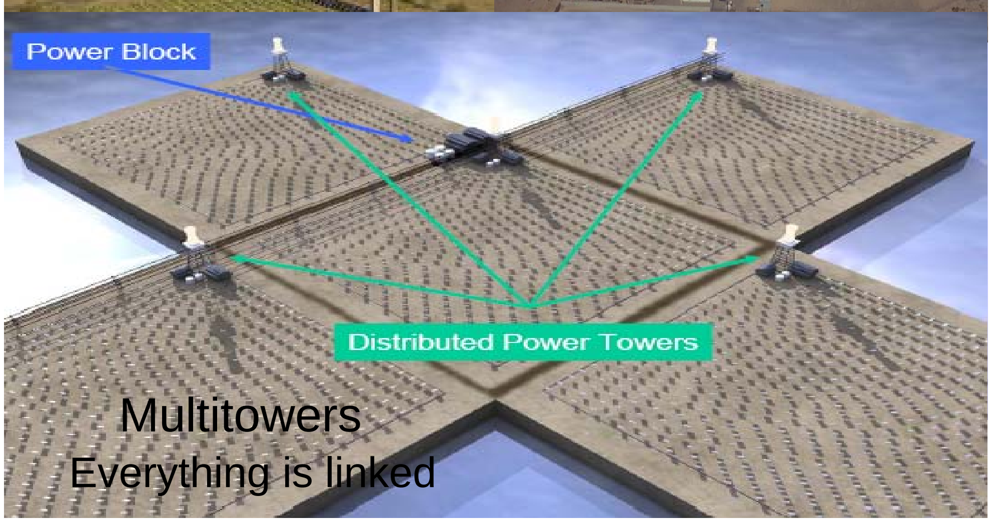




Solar Field designs & Relationship with receiver

(Receiver may be placed on Top)





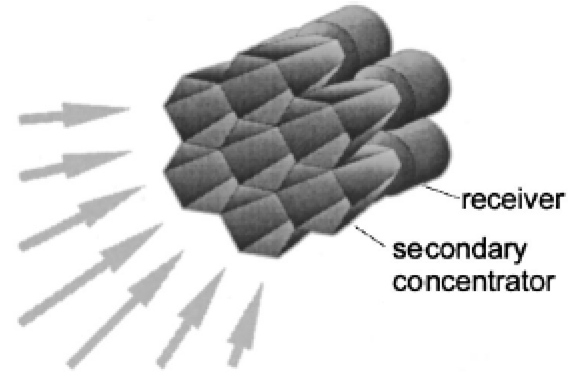
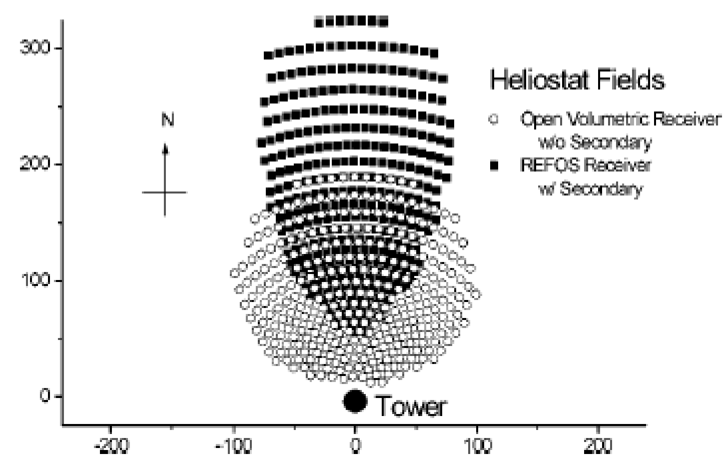


Fig. 2 Modular receiver arrangement

Tower The use of re-concentrators modifies the field arrangement: and

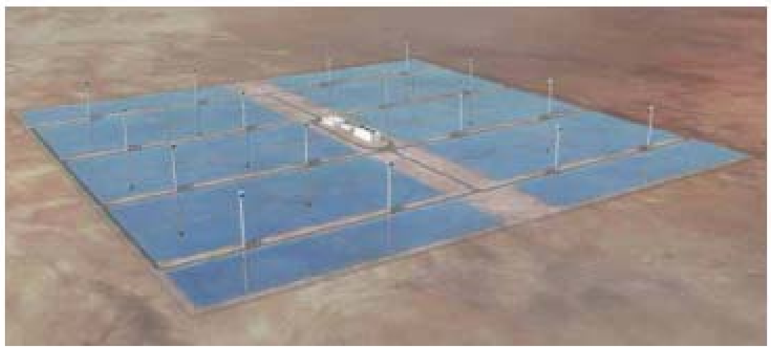


Tow

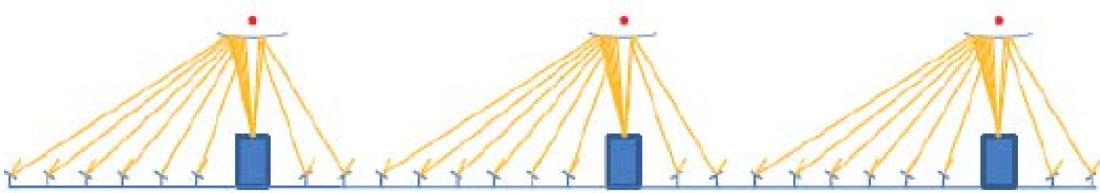
Fig. 13 Effect of Secondary Concentrator

Towers

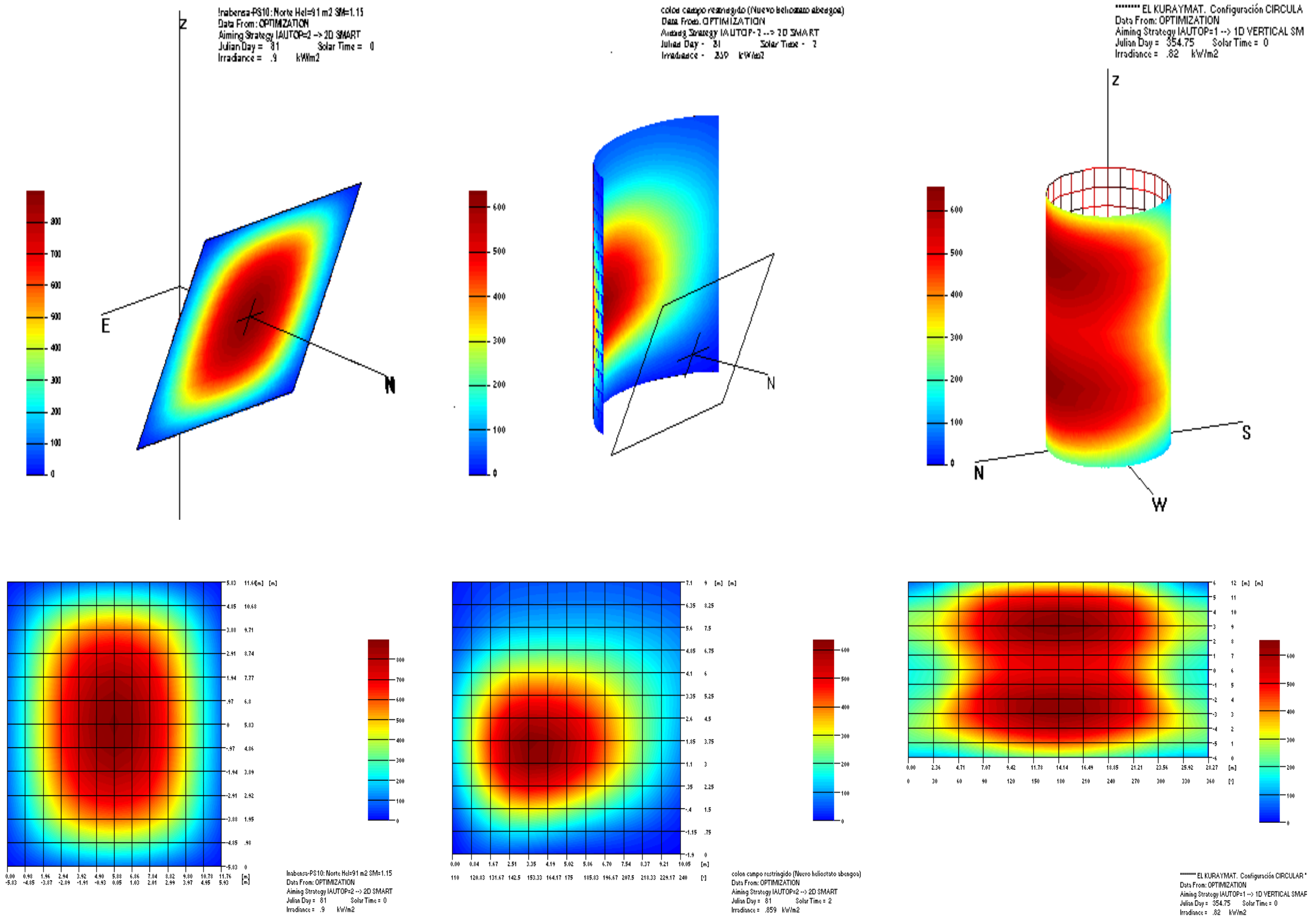
- Historical wisdom of 1 tower/plant is being challenged
  - 16 towers to produce 46 MW_e (eSolar)
    - Factory-made “wind-turbine-type” towers




  - Multiple beam-down towers to produce >20 MW_e (Tokyo Tech)
    - Single tower 100 kW_t demo will be operating 12/09




Solar field – receiver relationship: Concentrated solar flux distribution on aperture



Flat Plate Receiver

Cavity Receiver

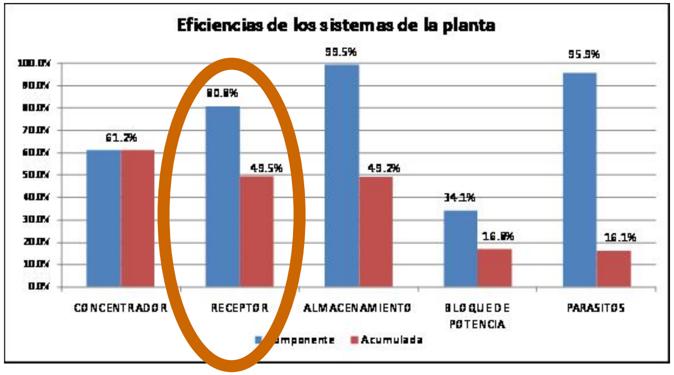
Cylindrical External Receiver

Non-homogeneous flux distributions over the receiver decreases the efficiency and the life time of receiver (thermal stress)

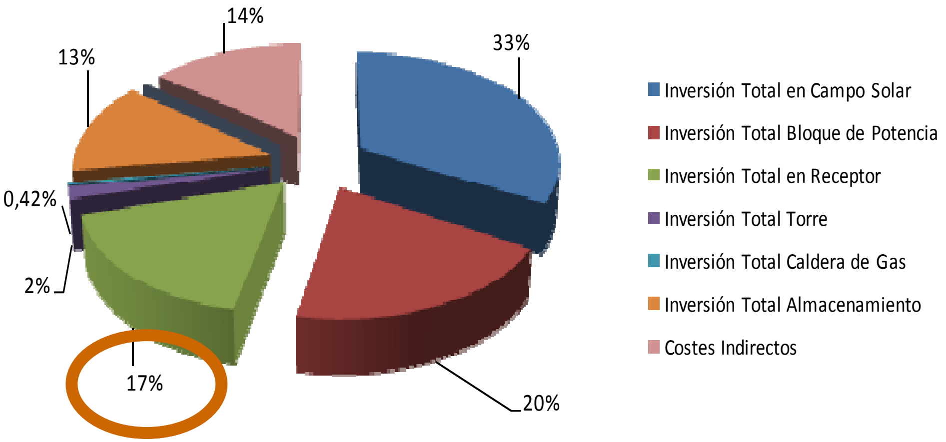
The Receiver is a key component

The receiver is a **key sub-component** in the development of Central Receiver technology. From several points of view:

- Concentrates most of the perception of "**technological risk**" attributable to the technology
- it may represent a significant part of the **investment cost** (ie ~ 17% in Gemasolar)
- Its **efficiency** is a proportional factor in overall plant performance (~ total electricity)
- Its **design continues being a challenge for engineering** (since that each design solution is tailor-made accounting for a large set of constrains)



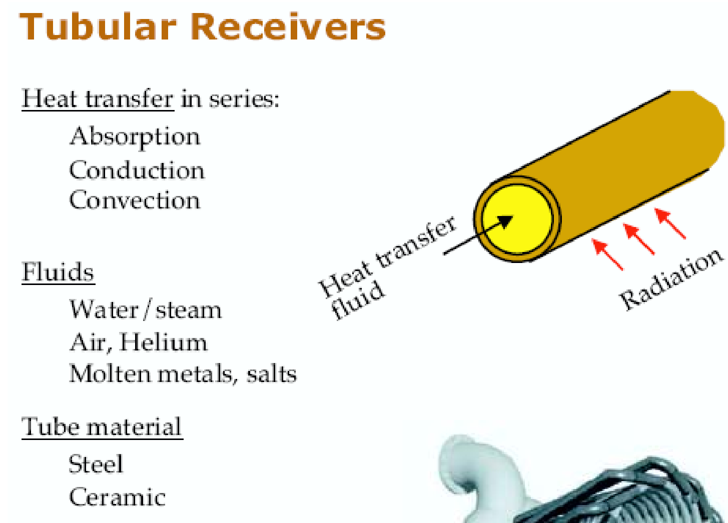
Distribución de los costes de inversión

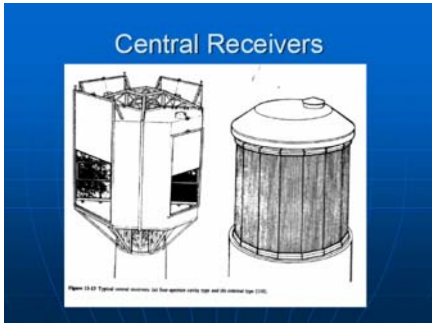


Two typologies of Receiver/absorber: Tubes and Volumetric

The choice of the **receiver type** and design may attend to **several constrains** and design requirements, like:

- **High absortivity** (ideally ~black body)
- The **working fluid** choice
- The nominal conditions in **temperature and solar flux**
- The placement in **relationship to the solar field,**
- The “optimal” **rate** among Performance/cost/Durability. (This implies an adequate choice of materials for corrosion and oxidation resistance, thermal stress resistance, cost,…)
- **Modularity** to reduce investment and Maintenance costs,
- Etc.





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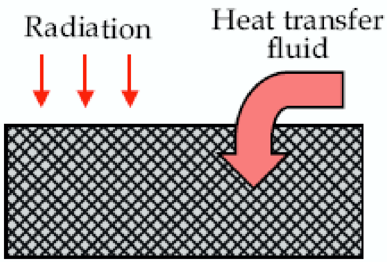
- Etc.

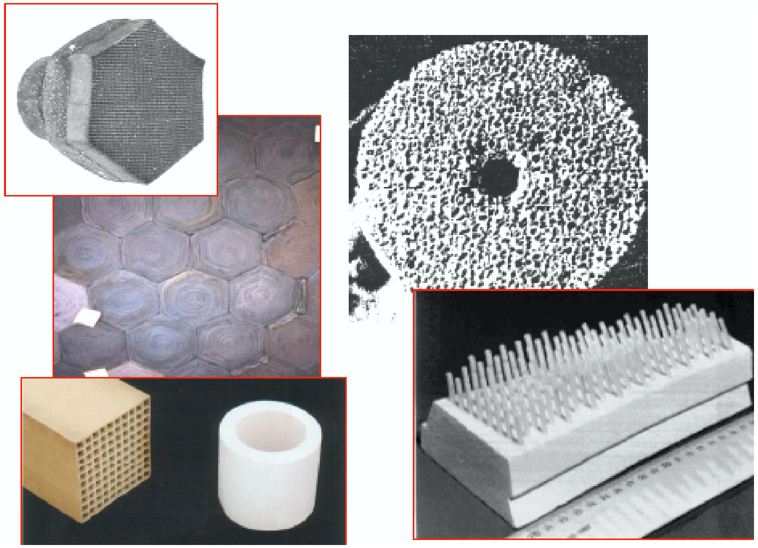
Volumetric Receivers

Heat transfer in series:
- Absorption
- Convection



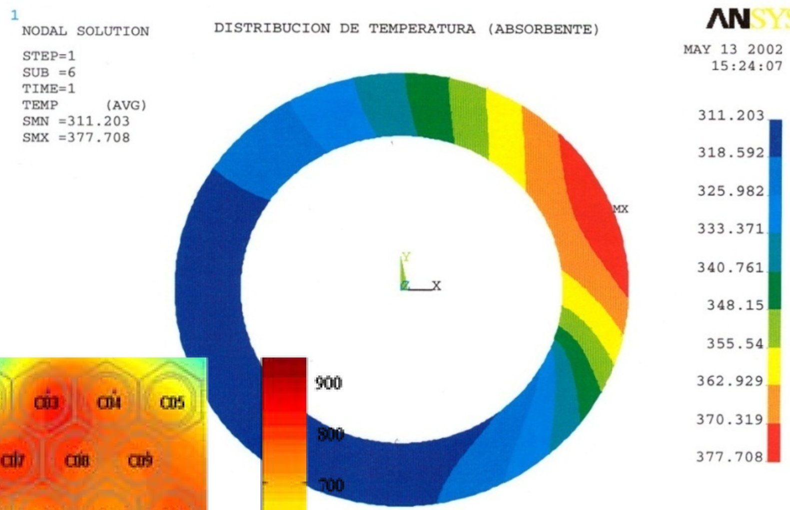
Fluids
- Air
- Other gas: closed

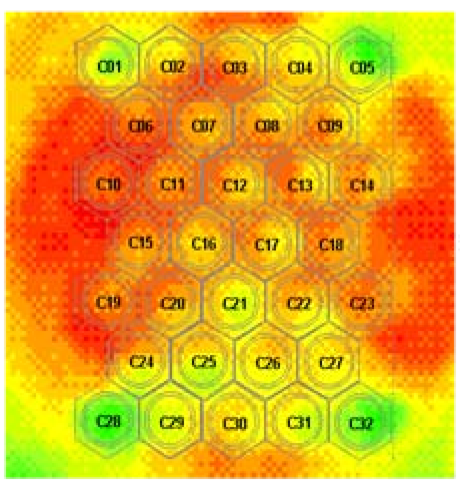
Absorber material
- Steel wire
- Ceramic pellets
- Ceramic foam

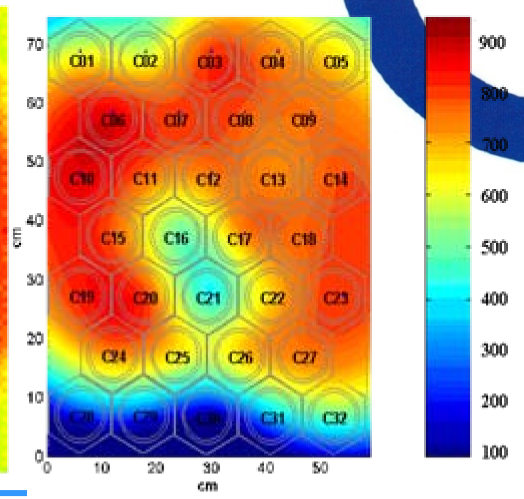


Technological risks in the Receiver ~ Technical factors associated to the high temperature and high solar flux

- **Controllability**
- **Stability**
- **Thermal stress**
- **Thermal gradients**
- **Durability**
- **Reliability**

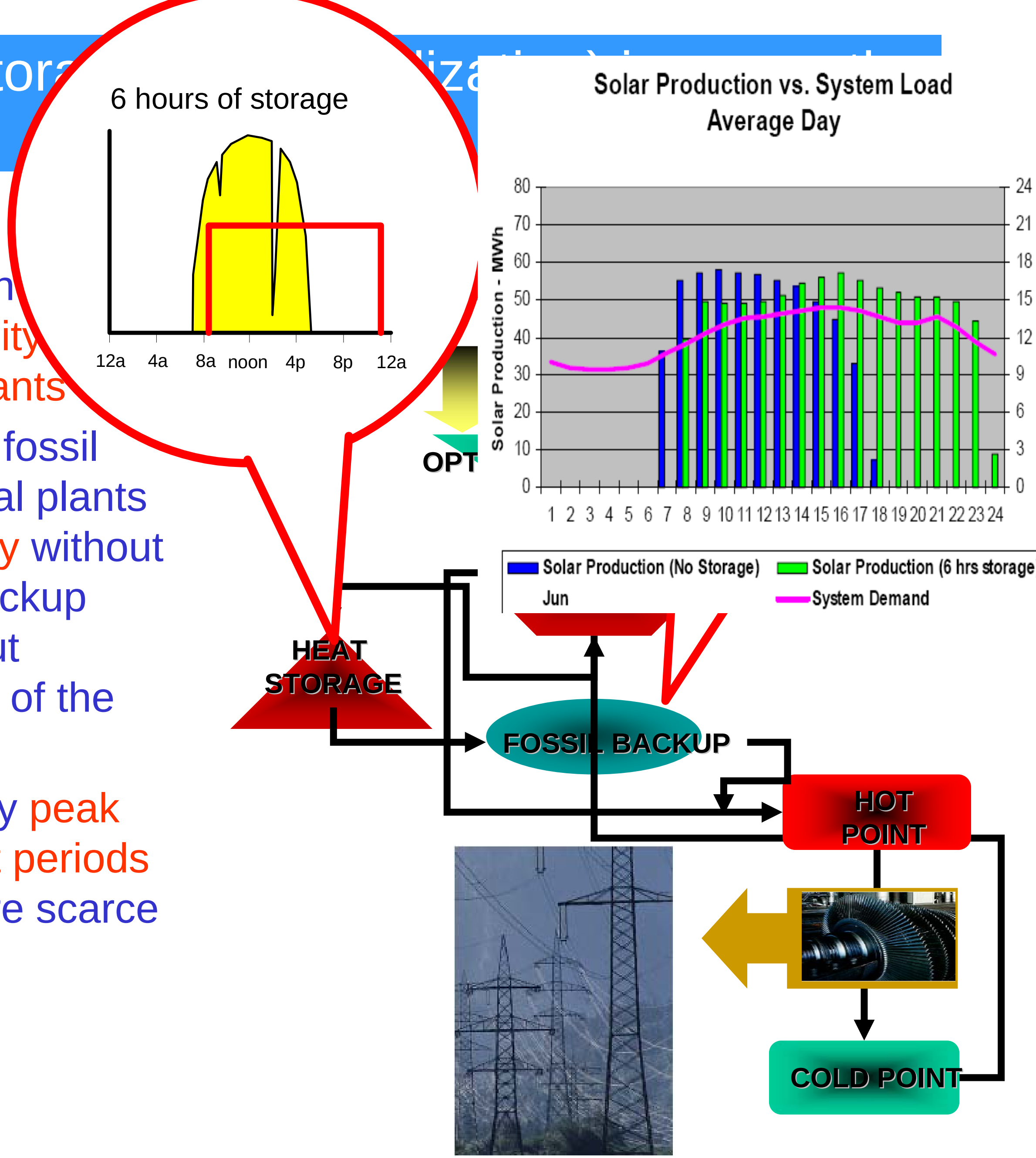




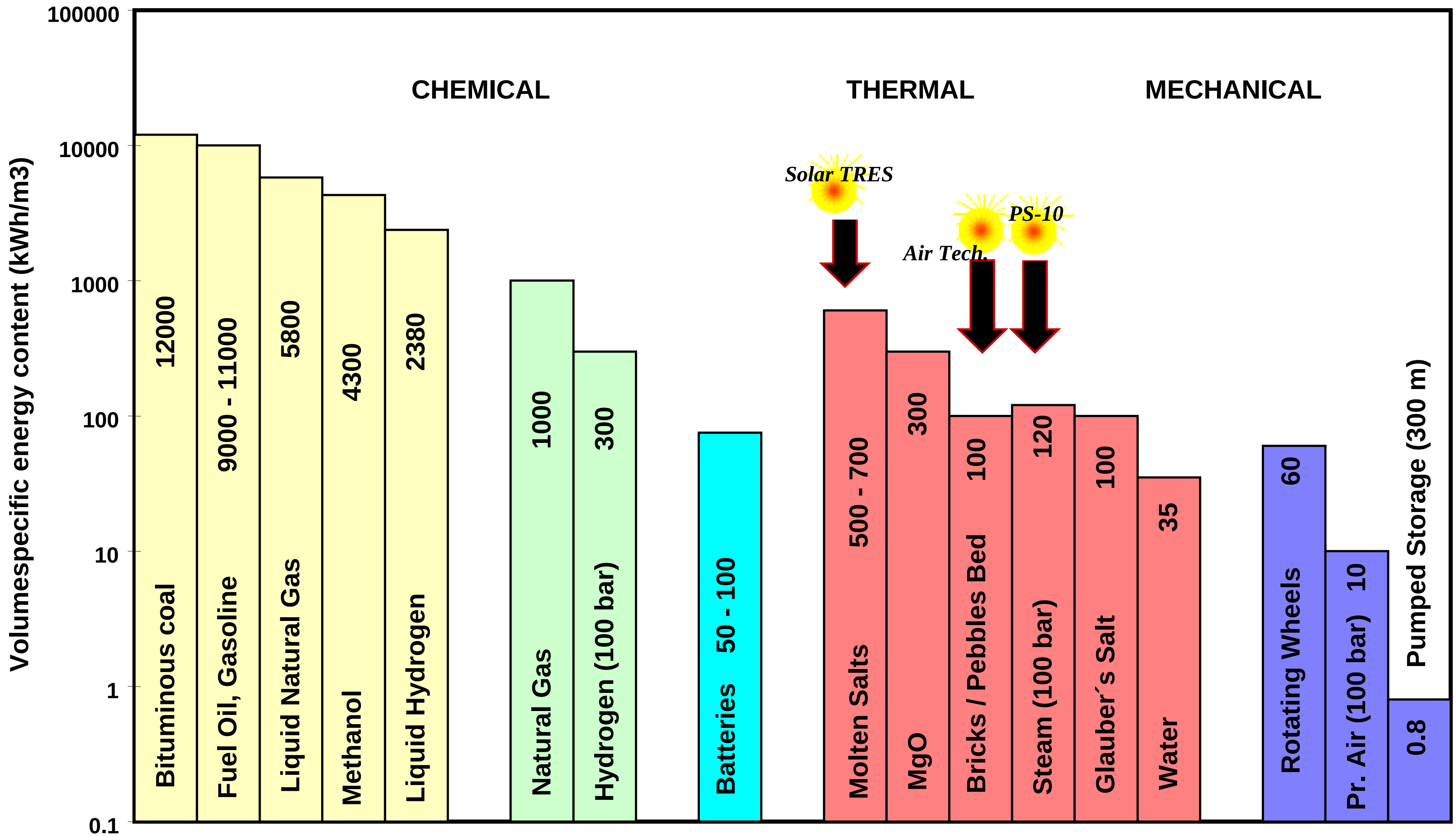


Heat stora… liza…

- CRS as other STE techn… have a unique integrability… conventional thermal plants
- With thermal storage or fossil fuel backup solar thermal plants can provide firm capacity without the need of separate backup power plants and without stochastic perturbations of the grid.
- Solar thermal can supply peak power in summerly heat periods when hydro and wind are scarce

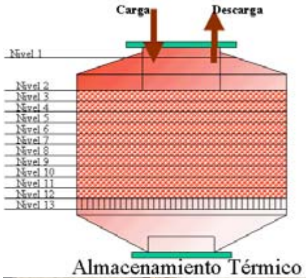


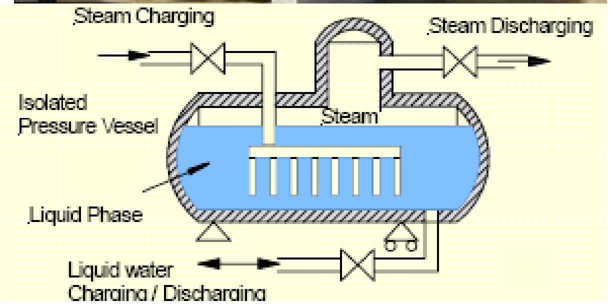
Capacity of Heat Storage options



Status of the CRS – Heat Storage

- **Heat storage (up to 15-20 hours) feasible with 2-tank molten salt and about 2-3 hours using pebbles-beds (for air technologies).**
- Heat storage for saturated or superheated steam is quite expensive and requires R&D.
- The cost goal is about **~20 €/kWh**



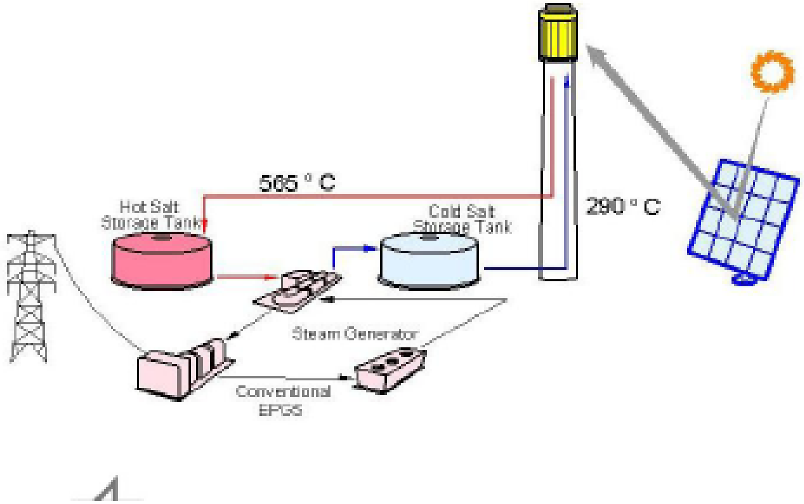


TSA

Heat storage using nitrate molten salts (indeed for CRS)

Molten Salt Storage

Commercial storage technology for solar tower plants



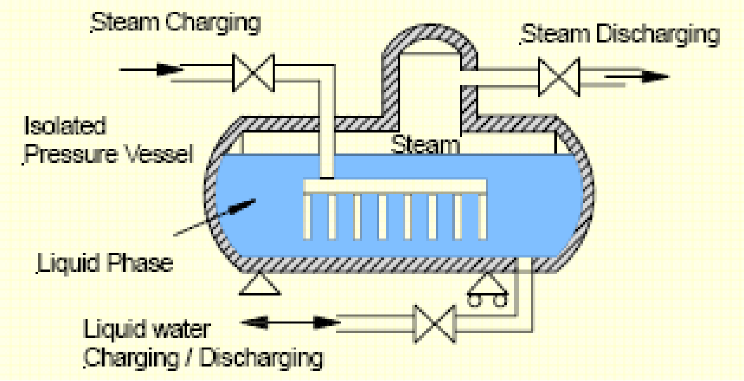
- preferred use for plant layout with molten salt HTF
- commercial systems with nitrate salts
- hot-cold tank design
- thermal capacity proportional to **ΔT**
- *investment cost ~ 10-20 $/kWh*

- risk of liquid salt freezing
- increased effort concerning trace heating, pumps, valves, gaskets etc.
- higher operation temperature limited by salt decomposition

Heat storage for water steam first implementations

Pressurized Water – Ruths Storage

for Water Steam Systems



- sensible pressurized water storage
- sliding pressure during discharge
- thermal capacity proportional to ΔT
- high investment cost caused by pressure vessel
- not really an option for large scale and high pressure application

Distinguished by the heat transfer fluid, there are three CRS options in competence:

	Direct Steam Generation	(Nitrate) Molten Salts	Atmospheric & Presurized Air
Operating Temperatura	< 290º C Saturated 290-550 ºC Superheated 550-650 ºC Supercrític	565 ºC	750-900ºC
Thermodinamic Cycle	Rankine (or integration as preheating in CC)	Rankine (or integration as preheating in CC)	Rankine / Brayton (or integration in top of CC)
Availability of Heat storage	¿! Presurized steam vesel ~ 30 mintos	Yes Two tanks (hot/cold) ~15 h	Yes Pebbles Beds (termocline) ~3 h
Capacity Factor (full load equivalent)	2.200 h/year	2200 - 5.700 h/year	3.500 h/year
Overall Annual Efficiency	13-16 %	14-18 %	14-18 %
Estimated cost of electricity	0,17-0,23 €/kWh-a	0,14-0,17 €/kWh-a	0,13-0,16 ¿? €/kWh-a
Commercial Situation (actuales / potenciales)	PS10, PS20 (Saturado), eSolar (Sobrec.) Brightsource E (Supercrit.)	Gemasolar/Solar Tres Rockedyne /SolarReserve Abu-Dhabi?	(1ª versión PS10) Pending ¡!

CRS with Water-Steam

CR with Direct Steam Generation

- Cheap, abundant heat transfer fluid with no environmental impact
- Not required Heat exchanger between solar receiver and Power block

Saturated Steam

Advantages:

- They have shown its feasibility (conventional boilers, Past demonstration projects –as CESA 1, …- and commercial CR plants PS10, …)
- Easy adaptation of conventional technologies
- Very low thermal losses (due to low temperature + cavity effect)

Disadvantages:

- Low efficiency of the PB

Superheated steam

Advantages:

- They may produce (for a same receiver/plant size) up to 20-30% more electricity than the saturated steam (due to the higher PB efficiency)

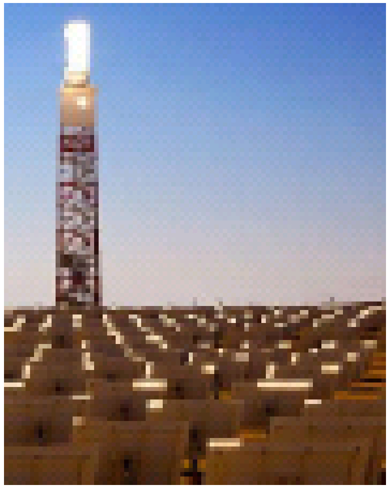
Disadvantages:

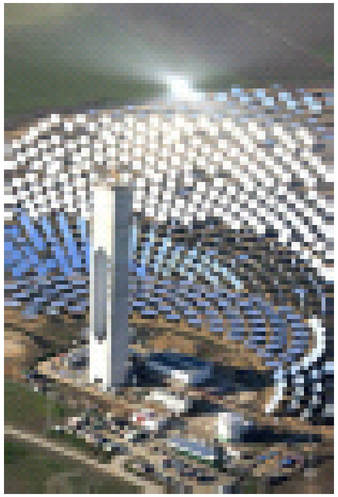
- Controllability in the receiver due to Phase change
- Technological risk lead to a recommendation of additional R&D
- More espensive materials (due to higher temperatures)

State of the art

- Resurrection of steam receiver technology
  - PS-10 MW$_e$ on grid 6/07, PS-20 5/09 (Abengoa)
  - 5 MW$_e$, 2-tower plant on utility grid 7/09 (eSolar)
  - 5 MW$_t$ thermal-only demonstration since late 08 (Brightsource)
  - Lessons learned from 10 MW$_e$ Solar One, shutdown in 1988
  - Steam receivers perceived as "low risk," many PPA's announced


eSolar

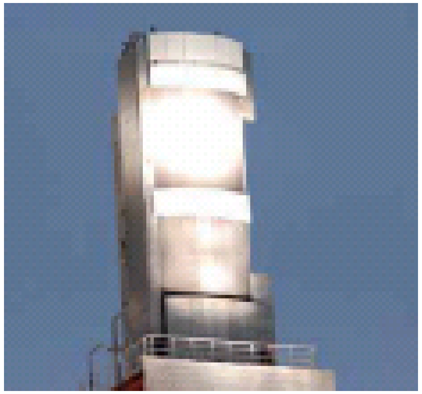

Brightsource


Abengoa

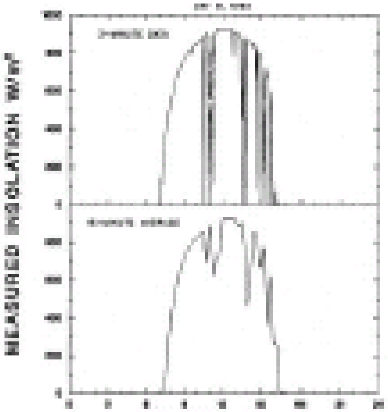
Steam Receivers

- Abengoa, Brightsource and eSolar plants are meeting their performance goals
  - Using recirculation-type boilers with superheat
    - Recommended for plants after Solar One

eSolar Dual Cavity



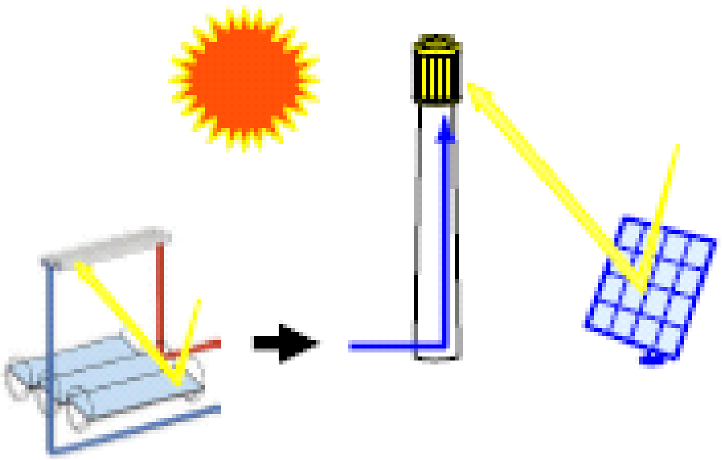
Brightsource Dual External



- Annual performance goal met at PS-10, others "to be determined"
  - Overprediction at Solar One
  - Needed 3-minute DNI data for accurate prediction
  - PS-10 backup fossil boiler improves "partly-cloudy" performance

STE-CR with Steam.
Ex. Optional scheeme

- Linear Fresnel/Tower System Study (CNRS/Bertin)
  - Fresnel provides evaporation (75% power)
  - Tower provides superheat (25% power)
  - Mismatch requires fuel boiler in parallel
  - Predicted LEC is 7% less than a trough plant

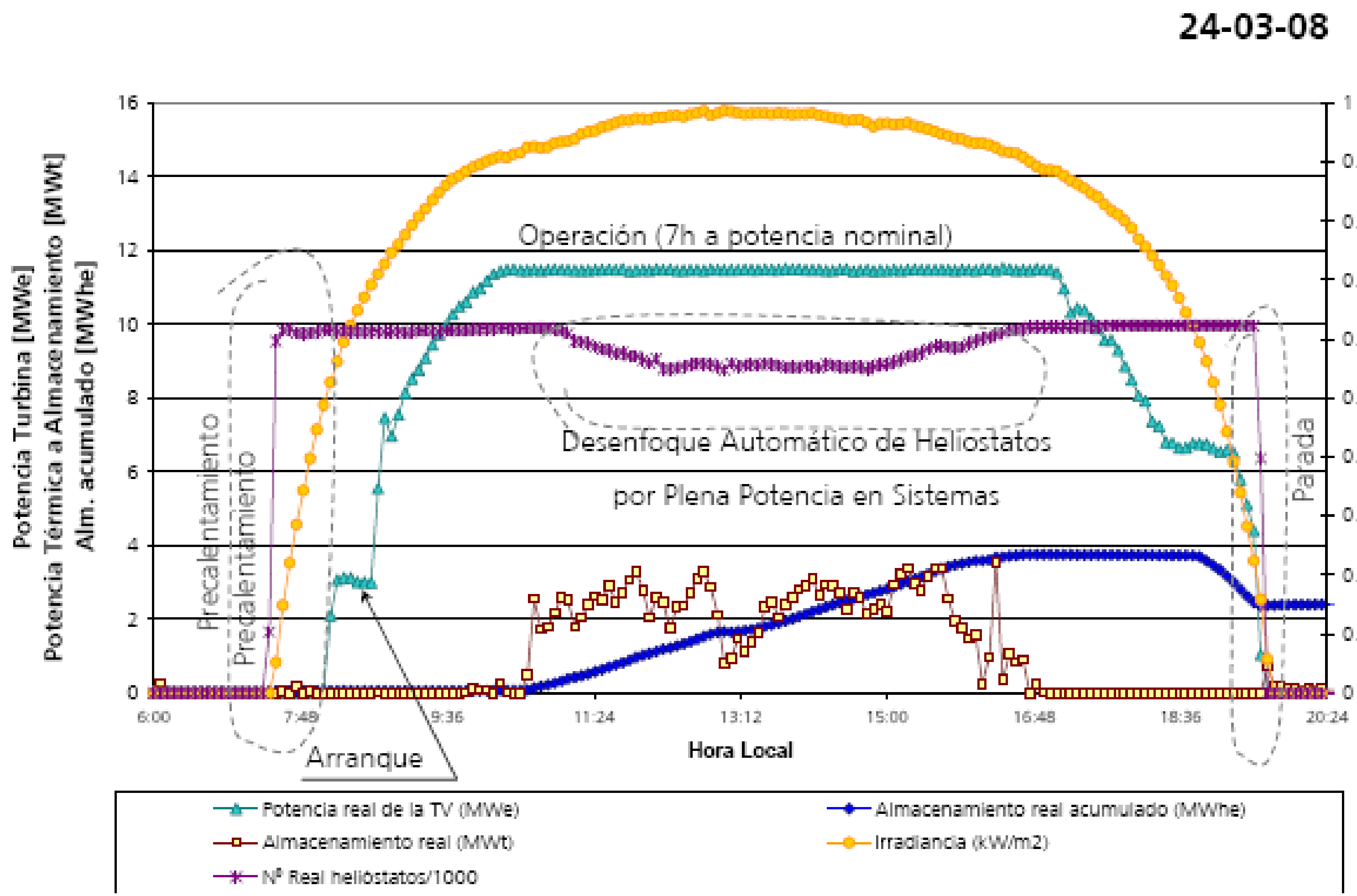


PS10 - PS20. Already in Commercial application

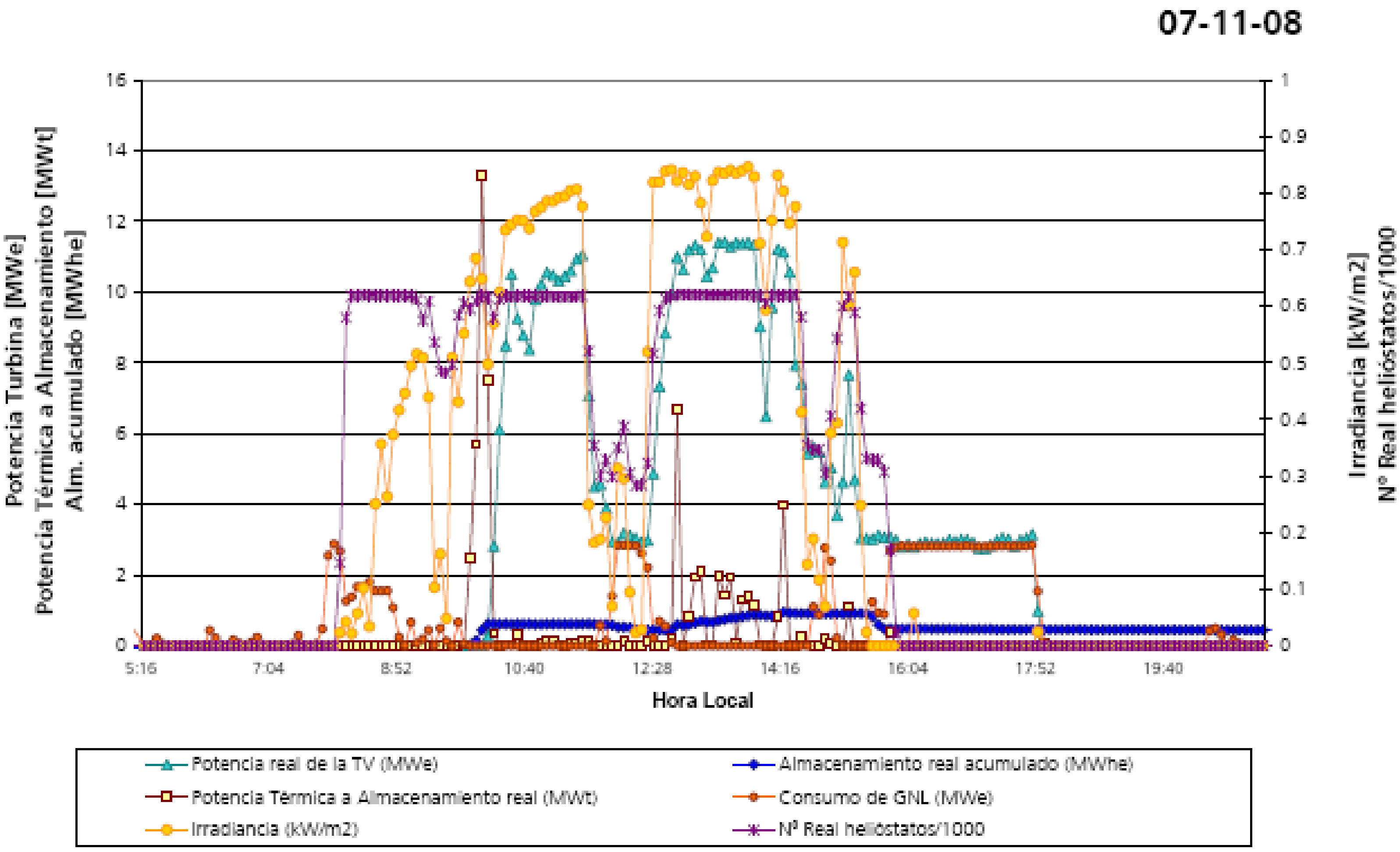
Daily Operation Phases:

- **1** – **Preheating** from the night resting time up to achieve the previous conditions for coupling to the turbine
- **2** – **Starting,** turbine connection and operating pressures stabilization.
- **3** – **Operation,** from power production stabilization upto stopping.
- **4** – **Stop,** actions carried out after depressurization up to turbine decoupling.
- **5** – **Hot re-starting**, after a transitory stop (shut down)

PS10 performance in a spring day



PS10. Operation in a day requiring support with gas

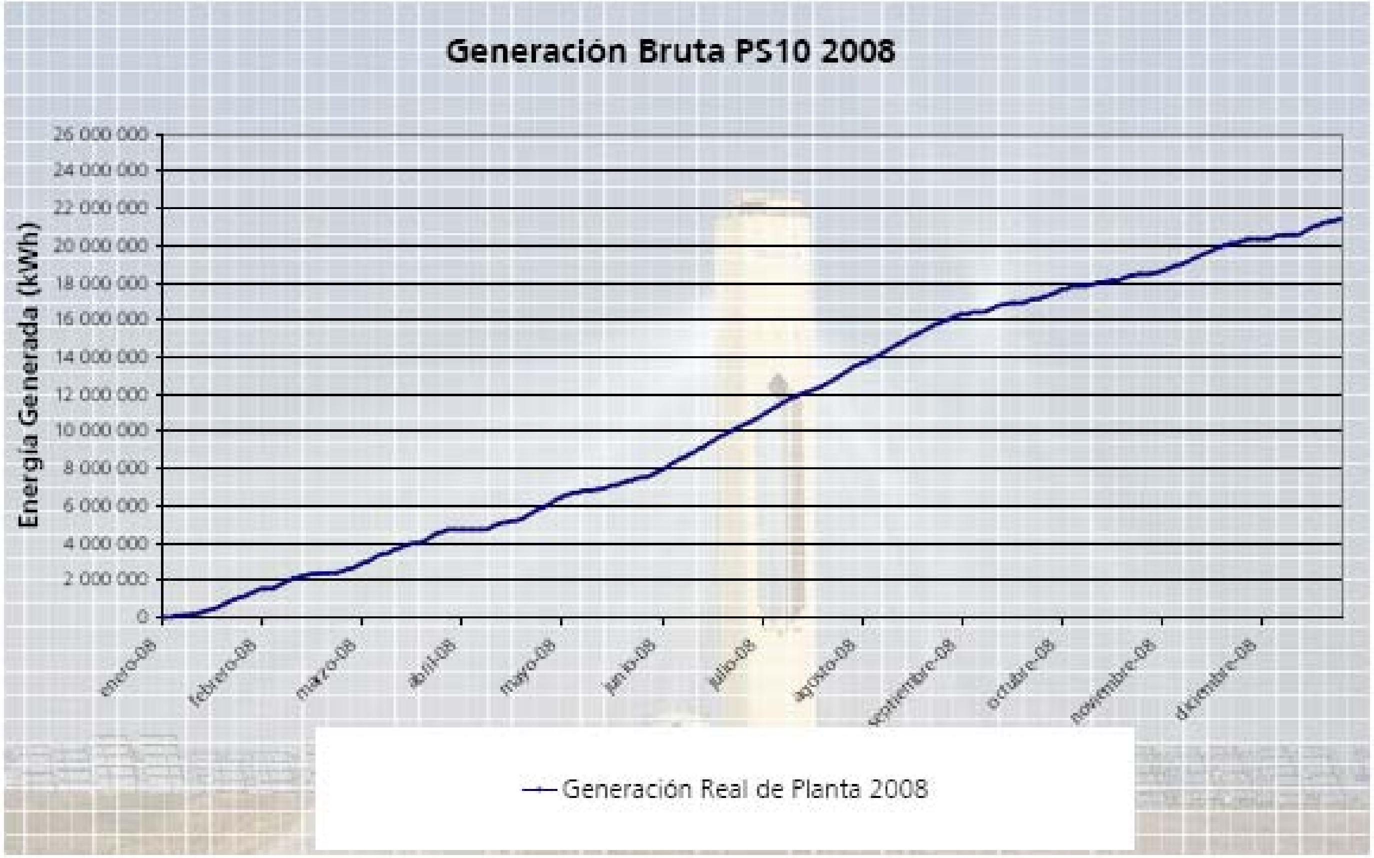


Availability

- PS10 has been in operation almost all the 6317 sunny hours since 21.06.07 up to 31.12.08.
- Total plant availability in this period is larger than 96%.
- Receiver availability in the period is larger than 99%.

Period	Operation Days	Mean Daytime Hours in a Day	Daytime Hours in Month	Operative Days (Plant)	Plant Operative Daytime Hours in Month	Plant Availability Factor	Operative Days (Receiver)	Receiver Operative Daytime Hours in Month	Receiver Availability Factor
21.06 to 30.06	10,0	14,58	145,80	10,0	145,80	100%	10,0	145,80	100%
Jul 07	31,0	14,35	444,85	28,5	408,98	92%	31,0	444,85	100%
Aug 07	31,0	13,45	416,95	31,0	416,95	100%	30,8	414,26	99%
Sep 07	30,0	12,22	366,60	30,0	366,60	100%	30,0	366,60	100%
Oct 07	31,0	11,15	345,65	31,0	345,65	100%	30,6	341,19	99%
Nov 07	30,0	9,95	298,50	30,0	298,50	100%	30,0	298,50	100%
Dec 07 (considering 15 Days Maintenance Stoppage)	16,0	9,42	150,72	10,0	94,20	63%	16,0	150,72	100%
Total 2007	**179,0**	**NA**	**2.169,07**	**170,5**	**2.076,68**	**95,7%**	**178,4**	**2.161,92**	**99,7%**
Jan 08	31,0	9,68	300,08	31,0	300,08	100%	31,0	300,08	100%
Feb 08	29,0	10,62	307,98	29,0	307,98	100%	29,0	307,98	100%
Mar 08	31,0	11,72	363,32	29,0	339,88	94%	30,5	357,46	98%
Apr 08	30,0	13,16	394,80	24,9	327,68	83%	30,0	394,80	100%
May 08	31,0	14,15	438,65	31,0	438,65	100%	31,0	438,65	100%
Jun 08	30,0	14,58	437,40	29,8	434,48	99%	29,7	433,03	99%
Jul 08	31,0	14,35	444,85	31,0	444,68	100%	30,9	442,84	100%
Ago 08	31,0	13,45	416,95	31,0	416,95	100%	31,0	416,95	100%
Sep 08	30,0	12,22	366,60	27,1	331,22	90%	29,0	354,38	97%
Oct 08	31,0	11,15	345,65	31,0	345,65	100%	31,0	345,65	100%
Nov 08	30,0	9,95	298,50	30,0	298,50	100%	30,0	298,50	100%
Dec 08	31,0	9,42	292,02	27,0	254,34	87%	30,6	288,18	99%
Total 2008	**366,0**	**NA**	**4.406,80**	**263,8**	**4.240,10**	**96,2%**	**272,1**	**4.378,50**	**99,4%**
		Total Operative Hours			**6.316,77**			**6.540,42**	
					Total Plant Availability Factor	**96,1%**			
								Total Receiver Availability Factor	**99,5%**

Annual electricity production



Alpine Sun Tower: STE-CR (superheated steam, small heliostats, …) 92 MWe by eSolar in California

National Renewable Energy Laboratory
Concentrating Solar Power: Projects

Alpine SunTower

This page provides information on Alpine SunTower, a concentrating solar power (CSP) project, with data organized by background, participants, and power plant configuration. Pacific Gas and Electric Company has entered into an agreement with Alpine SunTower, LLC, a subsidiary of NRG Energy, for 92 megawatts of renewable, solar thermal power. The Alpine SunTower project features eSolar's modular, scalable solar thermal technology and is scheduled for completion in 2012.

Project Overview

Project Name:	Alpine SunTower
Country:	United States
Location:	Lancaster, California (Antelope Valley)
Owner(s):	
Technology:	Power tower
Turbine Capacity:	Net: 92.0 MW
Status:	Under development
Start Year:	2012

Do you have more information, corrections, or comments?

Status Date: November 6, 2009

Background

Technology:	Power tower
Status:	Under development
Country:	United States
City:	Lancaster
State:	California
Region:	Antelope Valley
Electricity Generation:	192,000 MWh/yr
Start Production:	2012
PPA/Tariff Date:	June 25, 2009

Participants

Developer(s):	NRG Energy
Generation Offtaker(s):	Pacific Gas & Electric (PG&E)

Plant Configuration

Solar Field

Heliostat Manufacturer:	eSolar

Power Block

Turbine Capacity (Net):	92.0 MW

Ivanpah: 440 MWe (by Brightsource ~Luz2) in California (superheated steam)

National Renewable Energy Laboratory
Concentrating Solar Power: Projects

Ivanpah Solar Electric Generating Station

This page provides information on Ivanpah Solar Electric Generating Station , a concentrating solar power (CSP) project, with data organized by background, participants, and power plant configuration.

Project Overview

Project Name:	Ivanpah Solar Electric Generating Station (Ivanpah)
Country:	United States
Location:	Primm, NV, California
Owner(s):	
Technology:	Power tower
Turbine Capacity:	Net: 440.0 MW Gross: 468.0 MW
Status:	Under development
Start Year:	2013

Do you have more information, corrections, or comments?

Status Date:	December 17, 2009

Background

Technology:	Power tower
Status:	Under development
Country:	United States
City:	Primm, NV
State:	California
County:	San Bernardino, CA
Lat/Long Location:	35°33' 8.5? North, 115°27' 30.97? West
Land Area:	4,073 acres
Solar Resource:	2,717 kWh/m ^{2}/yr
Source of Solar Resource:	NREL Solar Power Prospector
Electricity Generation:	1,079,232 MWh/yr (Expected/Planned)
Contact(s):	Andy Taylor
Company:	BrightSource Energy
Break Ground:	January 2010
Start Production:	October 2013
Construction Job-Years:	1896
Annual O&M Jobs:	90
Tariff Period:	20 to 25 years
Project Type:	Commercial Plant

Participants

Developer(s):	BrightSource Energy
EPC Contractor:	Bechtel Engineering
Generation Offtaker(s):	Pacific Gas & Electric; Southern California Edison

Plant Configuration

Solar Field

Heliostat Solar-Field Aperture Area:	2,295,960 m ^{2}
# of Heliostats:	214,000
Heliostat Aperture Area:	14.08 m ^{2}
Tower Height:	459 ft

Receiver Manufacturer:	Riley Power
Receiver Type:	Solar receiver steam generator
Heat-Transfer Fluid Type:	Water
Receiver Inlet Temp:	480°F
Receiver Outlet Temp:	1050°F
Receiver Temp. Difference:	570°F

Power Block

Turbine Capacity (Gross):	468.0 MW
Turbine Capacity (Net):	440.0 MW
Turbine Description:	Gross is 117 MW per unit; net is 110 MW per unit
Output Type:	Rankine
Cooling Method:	Dry cooling
Annual Solar-to-Electricity Efficiency (Gross):	28.72%
Fossil Backup Type:	Natural gas

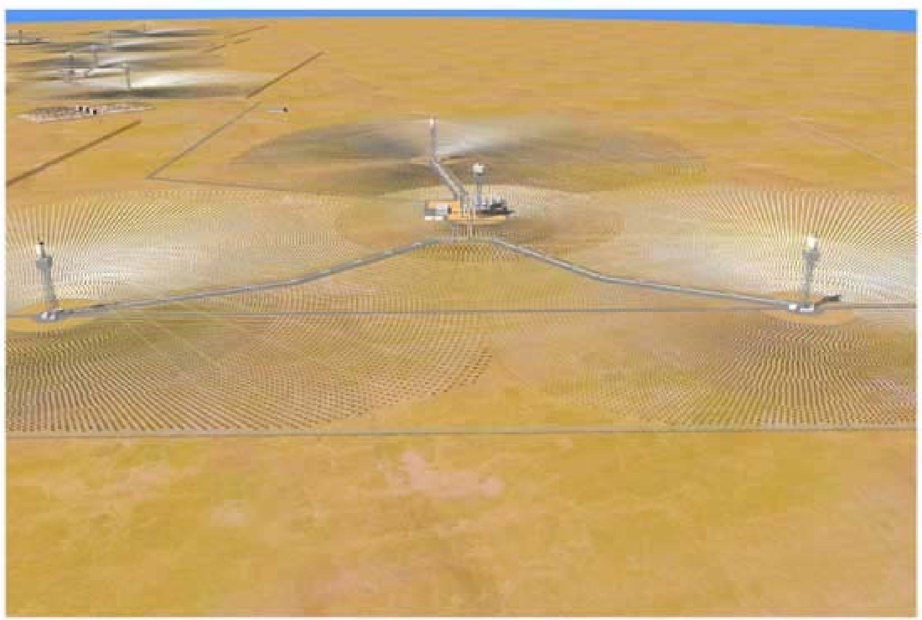
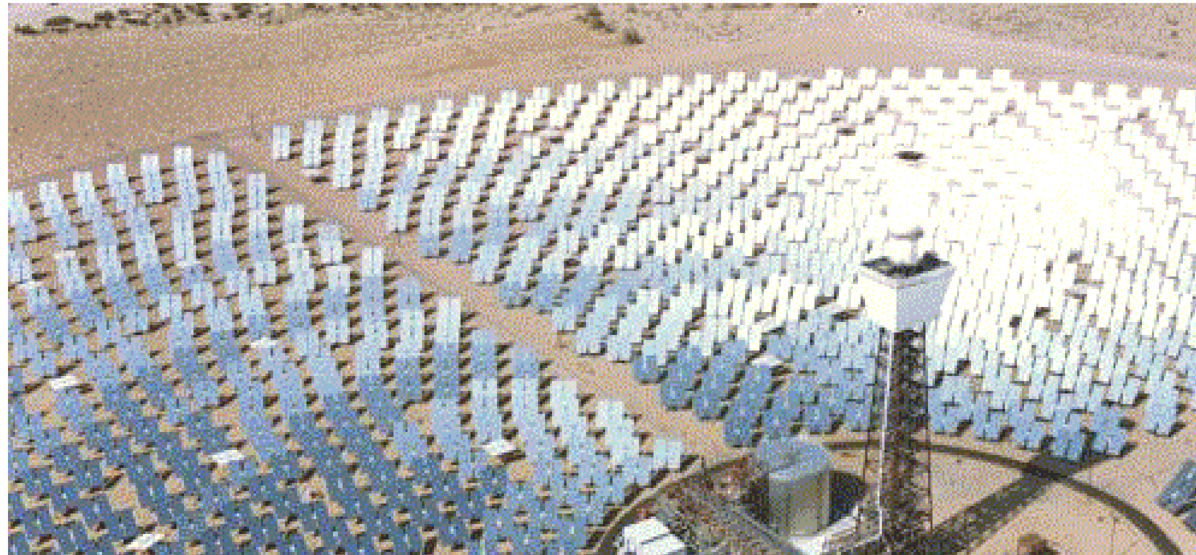


FIGURE 1.3-4
CLOSE-UP OF IVANPAH 1
IVANPAH SOLAR ELECTRIC GENERATING SYSTEM
CH2MHILL

CRS with Molten Salts

CRS with Molten Salts



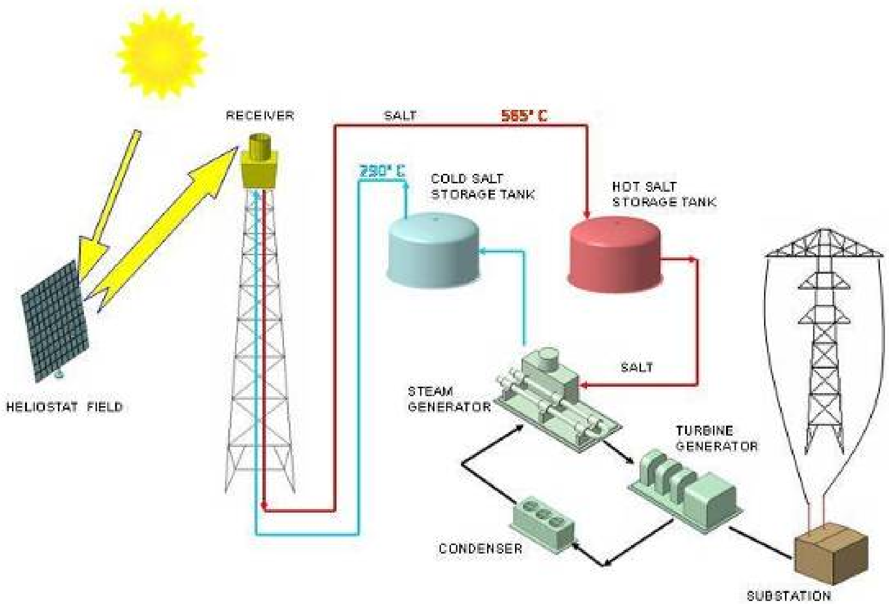
Advantages

- The molten salts may be used both to cool the receiver (as HTF) and as heat storage, thus, avoiding the use of a Heat exchanger.
- **Due to the high Capacity factors this seems be the most profitable solution for solar-only schemes**

Disadvantages:

- Operating temperatures are limited to the range 250-600 ºC
- It requires electrical tracing
- Risk of Salts Freezing

Molten salts receivers are being explored for CR and also for Parabolic Trough

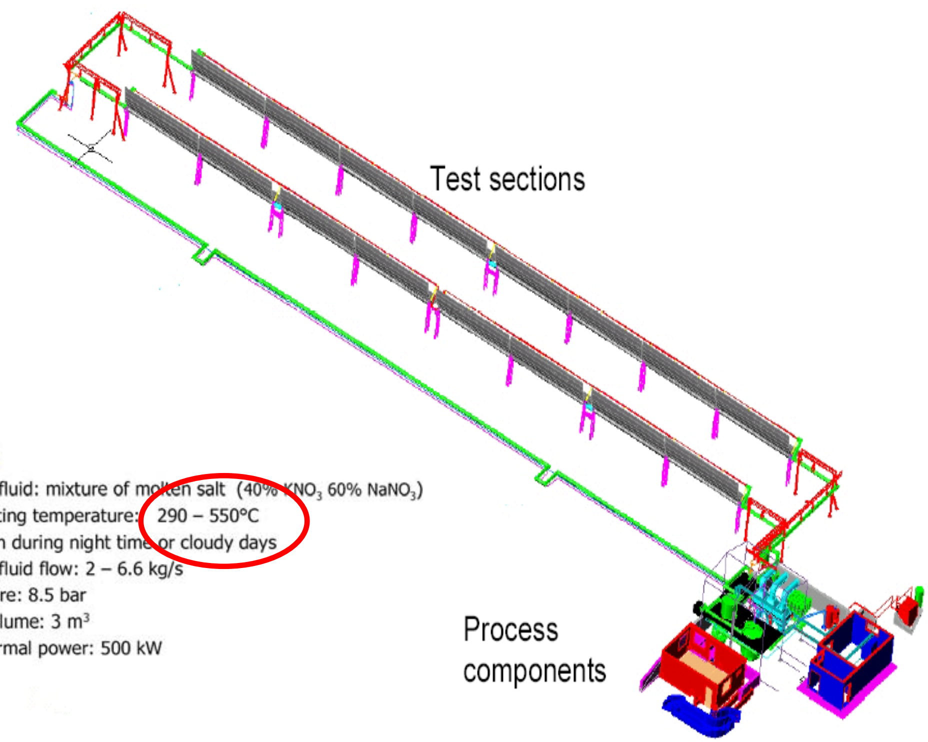


Central Receiver
(Torresol, SolarReserve, …)

ENEA Italian National Agency for New Technologies, Energy and the Environment

Solar Thermodynamic Project

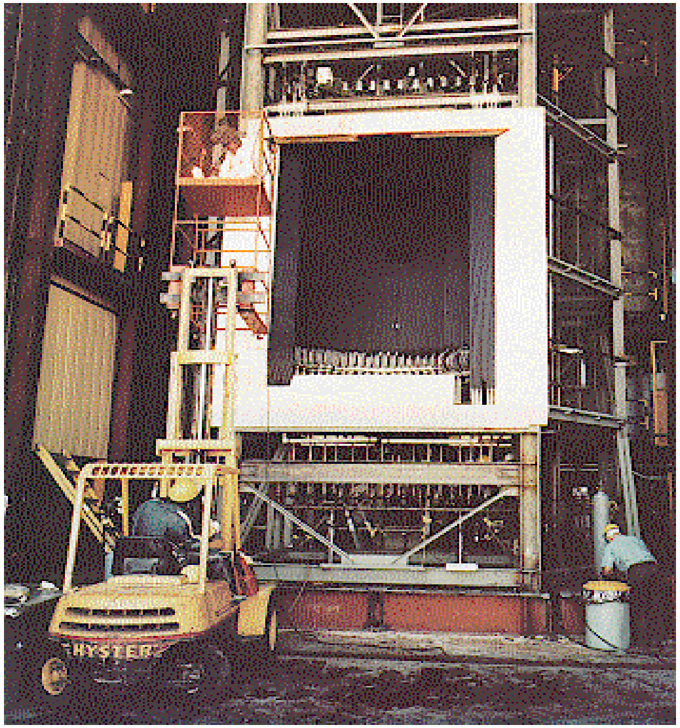
PCS test loop: aerial view



Main parameters

- Heat transfer fluid: mixture of molten salt (40% KNO_3 60% $NaNO_3$)
- Normal operating temperature: 290 – 550°C
- Fully operation during night time or cloudy days
- Heat transfer fluid flow: 2 – 6.6 kg/s
- Design pressure: 8.5 bar
- Molten salt volume: 3 m[3]
- Maximum thermal power: 500 kW

Precedent Molten Salts receivers



- **Receptores de Sales**
  - Temperatura Salida Fluido 566° C
  - Flujo incidente 400 kW / m²
  - Máximo Teórico 800 kW/m²
  - Eficiencia 85-90% (SIT)

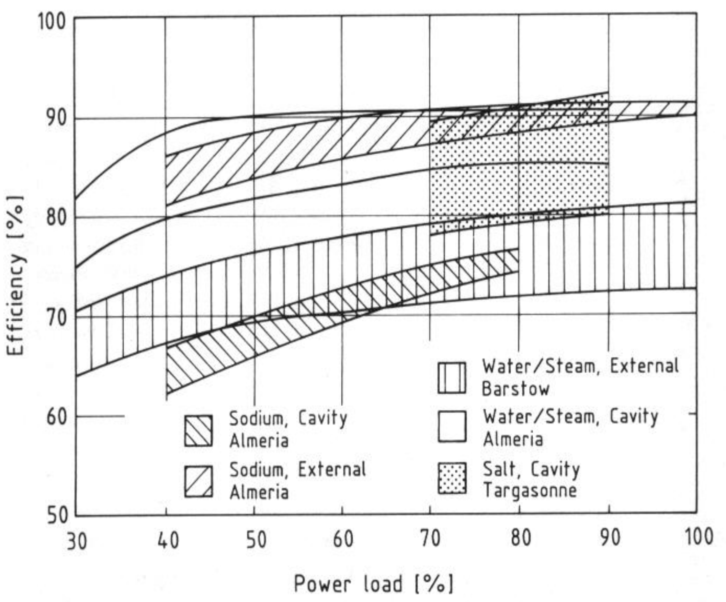
Receptor MSEE Albuquerque (Nuevo Mexico)

Absorbedor: 3.8 m de ancho y 3.6 m de alto

Potencia: 5 MW térmicos

Apertura: 2.1 m de ancho por 3.6 m de alto

Precedent Molten Salts receivers



Receptor cavidad con 16 m2 apertura

Temperatura sales = 250/450ºC

Vapor 410ºC y 40 bar

Central Themis en Targasonne (Francia)

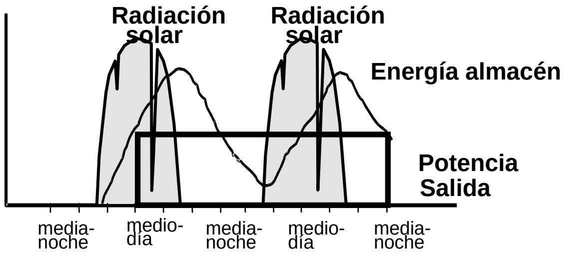
Potencia: 2,5 MWe

201 helióstatos y 10.740 m2

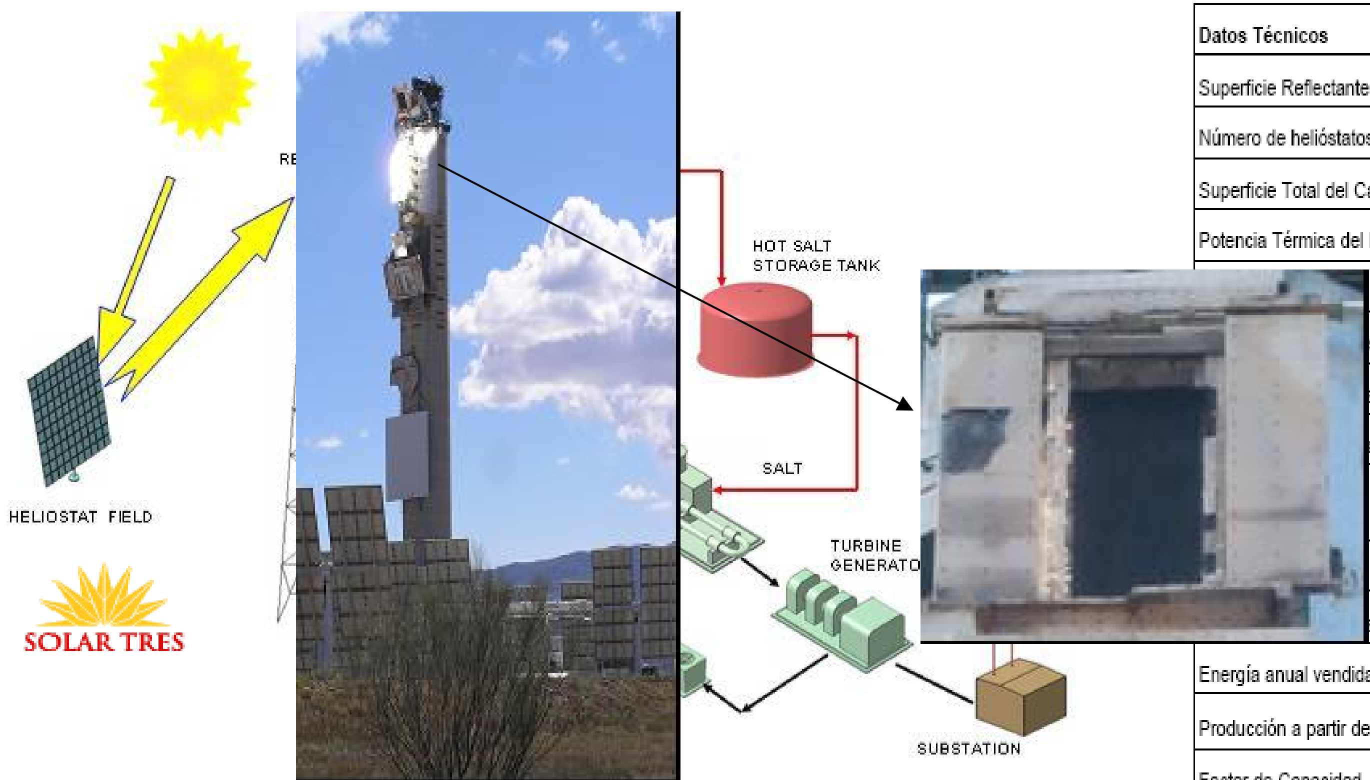
Torre 106 m

Precedent Molten Salts receivers

- 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 Tres / GEMASOLAR



Datos Técnicos	
Superficie Reflectante del Campo de Helióstatos	264825 m^2
Número de helióstatos	2750
Superficie Total del Campo de Helióstatos	142.31 Ha
Potencia Térmica del Receptor	120 MWt
	120 m
…namiento Térmico	15 horas
…a	17 MWe
…a de GN	16 MWt
…l directa anual sobre Helióstatos	2062 kWh/m^2
Energía anual vendida	105566 MWhe
Producción a partir de GN	15%
Factor de Capacidad	71%

- **Solar Tres** Project partially financed by the **European Commission** (with 5 M€; Contract No. NNE5/2001/369; with a consortium **SENER, CIEMAT, ALSTOM-SIEMENS, SAINT GOBAIN y GHERSA.**
- Sener & Ciemat (with a budget of 6 M€) **validated the receiver Technology**
- **TORRESOL** promotes the **GEMASOLAR** Power plant (Next speech)

STE-CR with Molten salts and large heat storage constitute (maybe) the most promising option for «solar electricity»

Molten Salts –(Other Tecnology Promoters: Solar Reserve/Rocketdyne (USA)

National Renewable Energy Laboratory
Concentrating Solar Power: Projects

Rice Solar Energy Project

This page provides information on Rice Solar Energy Project , a concentrating solar power (CSP) project, with data organized by background, participants, and power plant configuration.

Project Overview

Project Name:	Rice Solar Energy Project (Rice)
Country:	United States
Location:	Rice, California (Mojave Desert, near Blythe)
Owner(s):	SolarReserve's Rice Solar Energy, LLC (100%)
Technology:	Power tower
Turbine Capacity:	Net: 150.0 MW
Status:	Under development
Start Year:	2013

Do you have more information, corrections, or comments?

Status Date:	January 6, 2010

Background

Technology:	Power tower
Status:	Under development
Country:	United States
City:	Rice
State:	California
County:	Riverside
Region:	Mojave Desert, near Blythe
Land Area:	1,410 acres
Solar Resource:	2,598 kWh/m ²/yr
Source of Solar Resource:	NREL Solar Power Prospector
Electricity Generation:	450,000 MWh/yr (Expected/Planned)
Generation Data Explanation:	MWh/yr
Contact(s):	Tom Georgis; Jeff Benoit
Company:	SolarReserve
Key References:	Press Release
Break Ground:	2011
Start Production:	October 1, 2013
Construction Job-Years:	450
Annual O&M Jobs:	45
PPA/Tariff Date:	December 22, 2009
Project Type:	Commercial Plant

Participants

Developer(s):	SolarReserve's Rice Solar Energy, LLC
Owner(s) (%):	SolarReserve's Rice Solar Energy, LLC (100%)
EPC Contractor:	United Technologies Corp - Pratt Whitney Power Systems
Operator(s):	SolarReserve's Rice Solar Energy, LLC
Generation Offtaker(s):	Pacific Gas & Electric

Plant Configuration

Solar Field

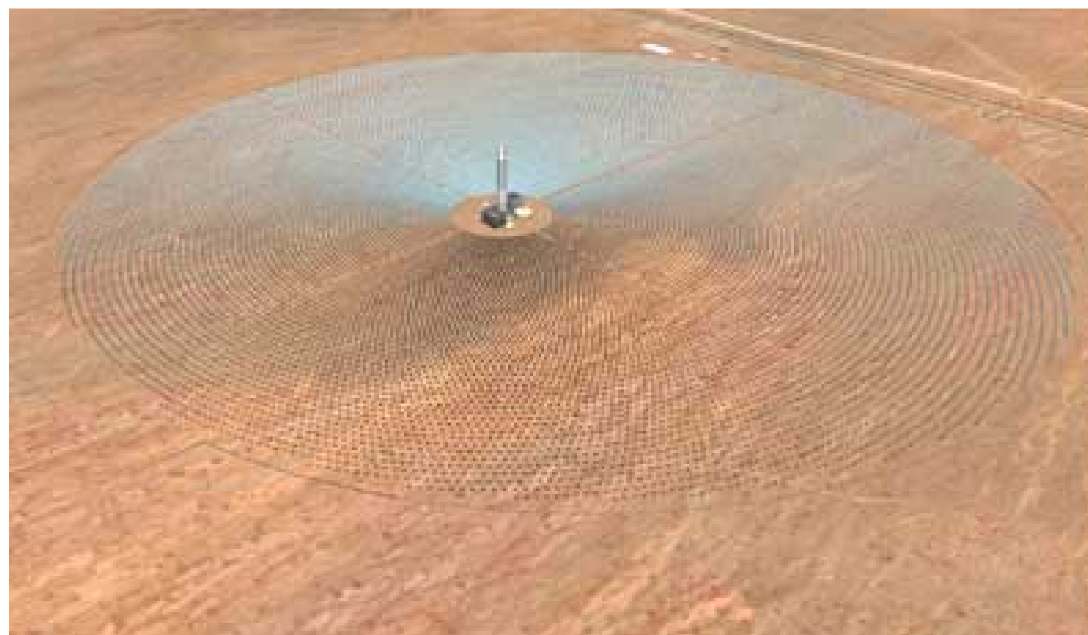
Heliostat Solar-Field Aperture Area:	1,071,361 m ²
# of Heliostats:	17,170
Heliostat Aperture Area:	62.4 m ²
Heliostat Manufacturer:	Pratt Whitney
Tower Height:	540 ft
Receiver Manufacturer:	Pratt Whitney Rocketdyne
Receiver Type:	External - cylindrical
Heat-Transfer Fluid Type:	Molten salt
Receiver Inlet Temp:	550°F
Receiver Outlet Temp:	1050°F

Power Block

Turbine Capacity (Net):	150.0 MW
Output Type:	Rankine
Power Cycle Pressure:	115.0 bars
Cooling Method:	Dry cooling
Fossil Backup Type:	None

Thermal Storage

Storage Type:	Other
Thermal Storage Description:	Thermal energy storage achieved by raising salt temperature from 550 to 1050 F. Thermal storage efficiency is 99%



CRS with Air

CRS with Air

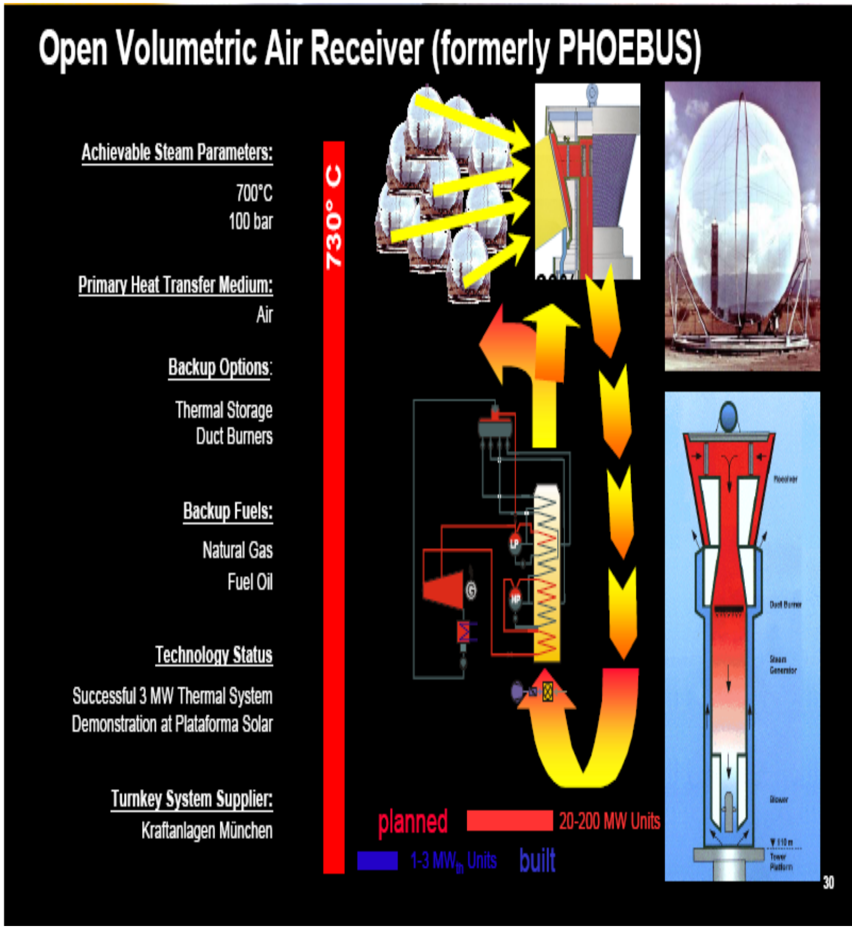
Advantages:

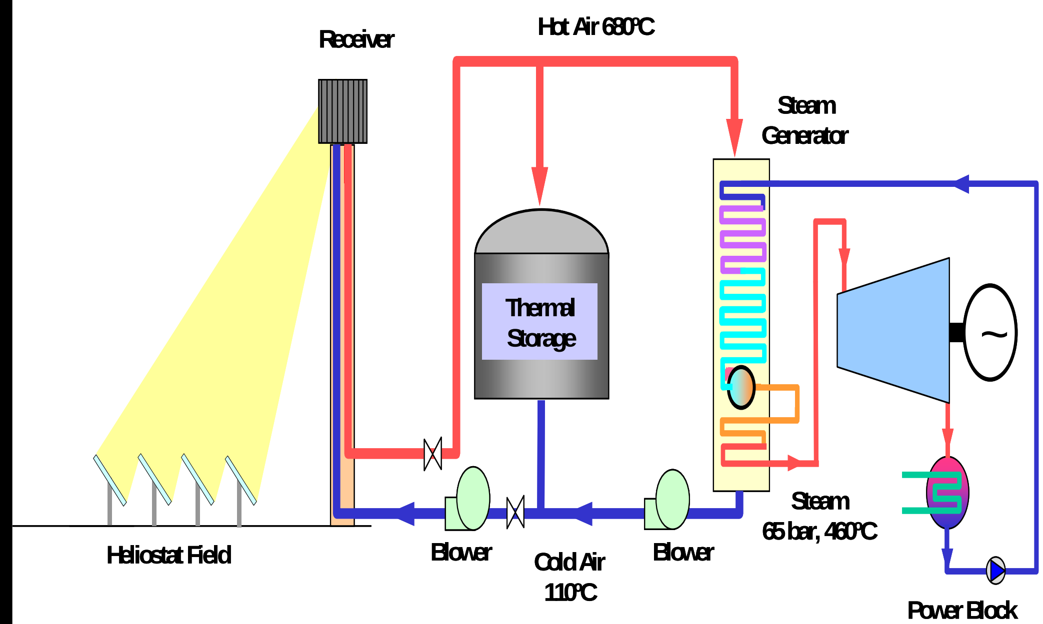
- Working fluid always available
- Good performance under solar transients
- Low thermal losses (due cavity effect of volumetric absorber)
- Very high working temperatures are feasible (1200 ºC achieved)
- …

Disadvantages:

- Air is not a very good heat transfer medium
- It is difficult to cool adequately (by air mass flow distribution) to obtain uniform temperature in the absorber aperture
- When requiring pressurized air there are pressure limitations and maximum sizes of quartz window
- Integration in C.C. feasible but not commercial

Plant scheme

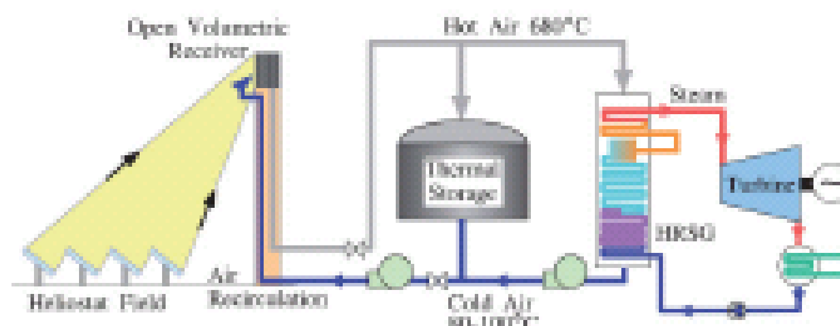




Volumetric Air Receivers

- 1.5 MW_e "Solar Tower Julich" on utility grid 4/09
  - Volumetric-air receiver R&D since late 1980's
  - Demo with goal of scaling up to 100 MW_e
  - German/Belgian "virtual institute" will lead test and evaluation and perform commercialization studies

VICERP

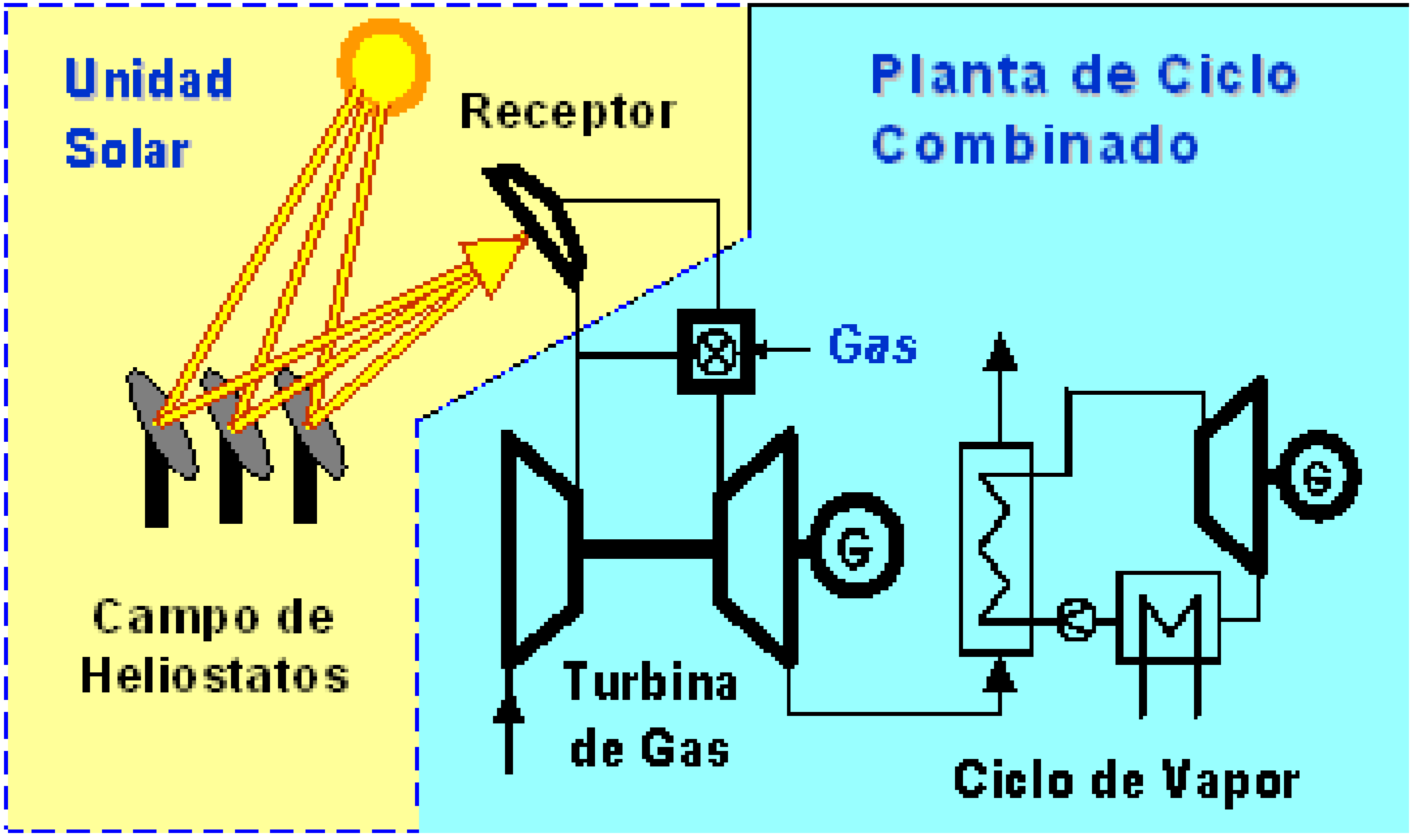


CRS with (pressurized) Air

SRC- Pressurized Air

Aimed for Solar Combined cycle

Project “Solgate”



STE-CR with Pressurized air

Air Pressure Technology

- Brayton cycle or combined type
- Limitations on receiver design and field of heliostats
- Limitations in size of receiver module by quartz window

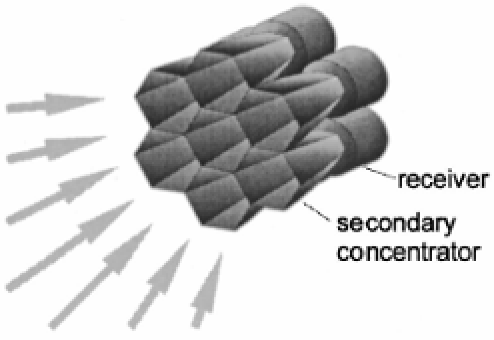
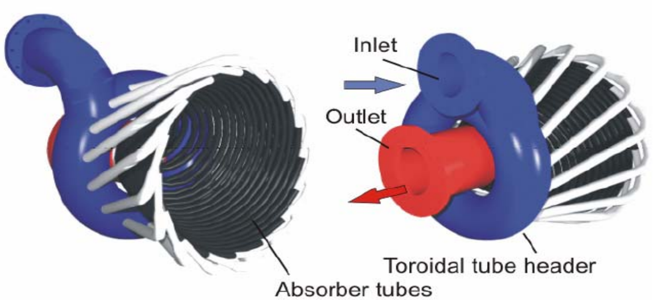


Fig. 2 Modular receiver arrangement



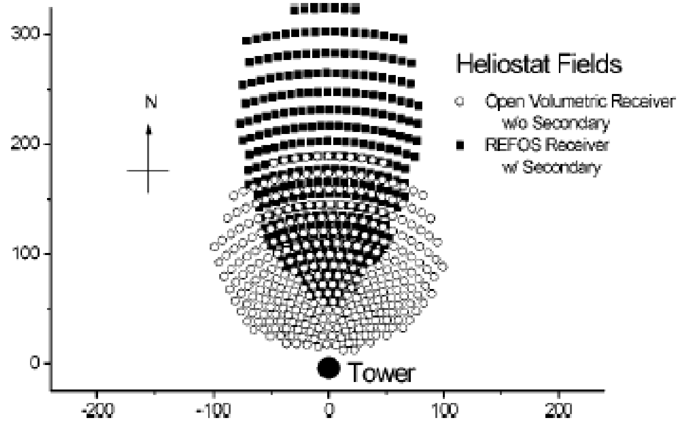
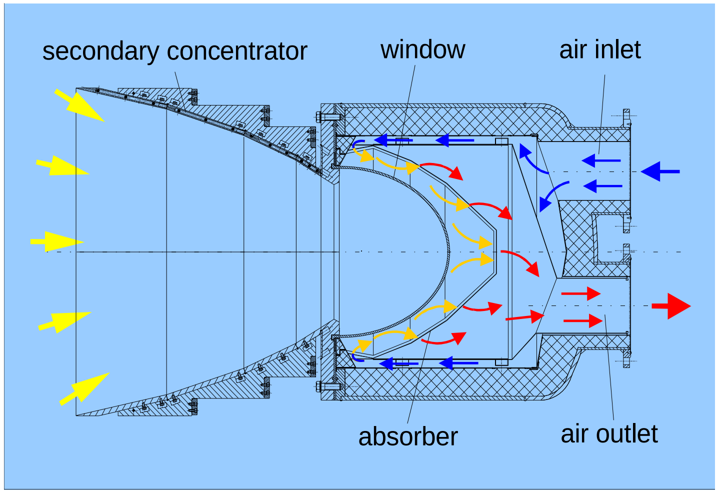
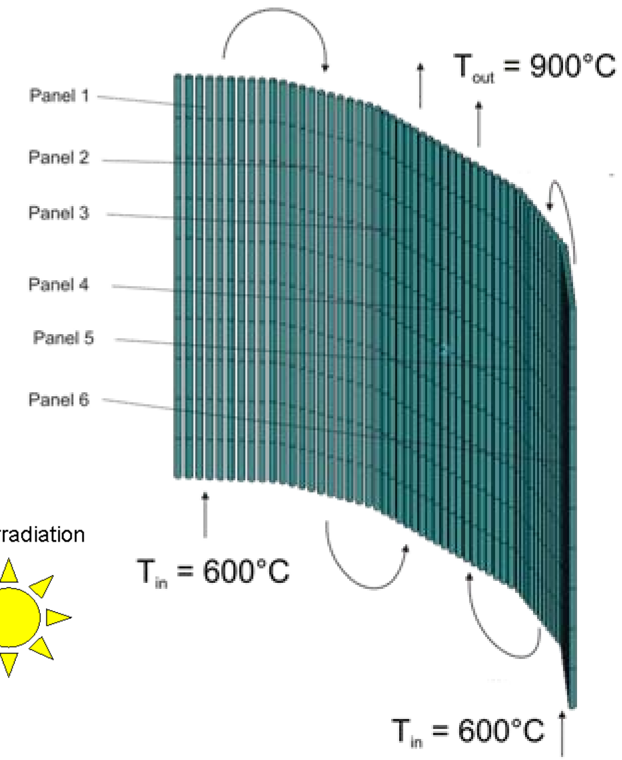
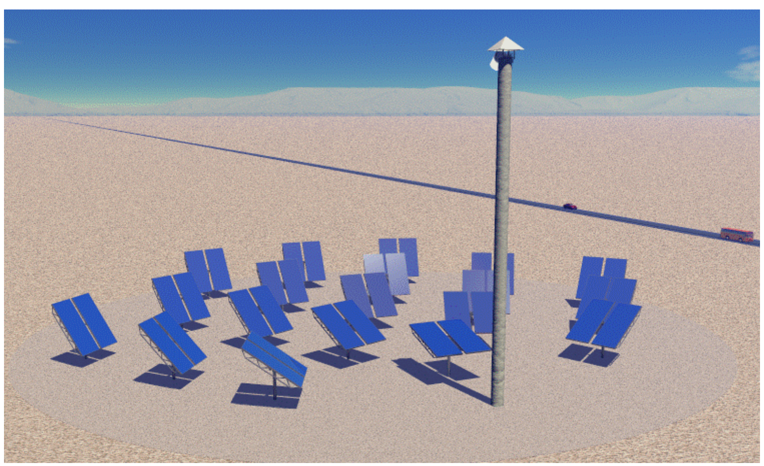


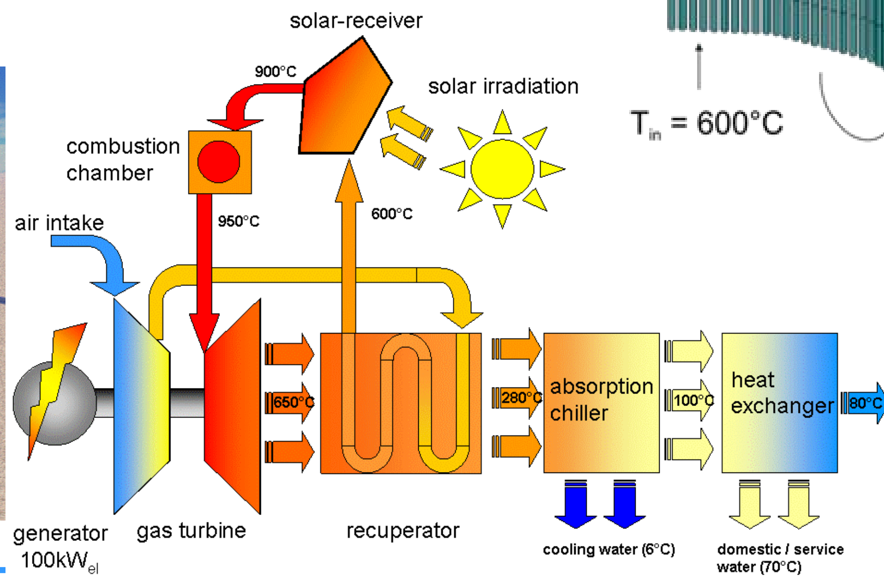
Fig. 13 Effect of Secondary Concentrator



- ➢Solarization of a commercial Gas turbine (100 kWe)
- ➢Tube receiver for presurized air
- ➢Allowing Co-generation, (e.g. Air conditioning and heating)
- ➢High overall efficiency
- ➢Status: prototype (+ development of new receiver)



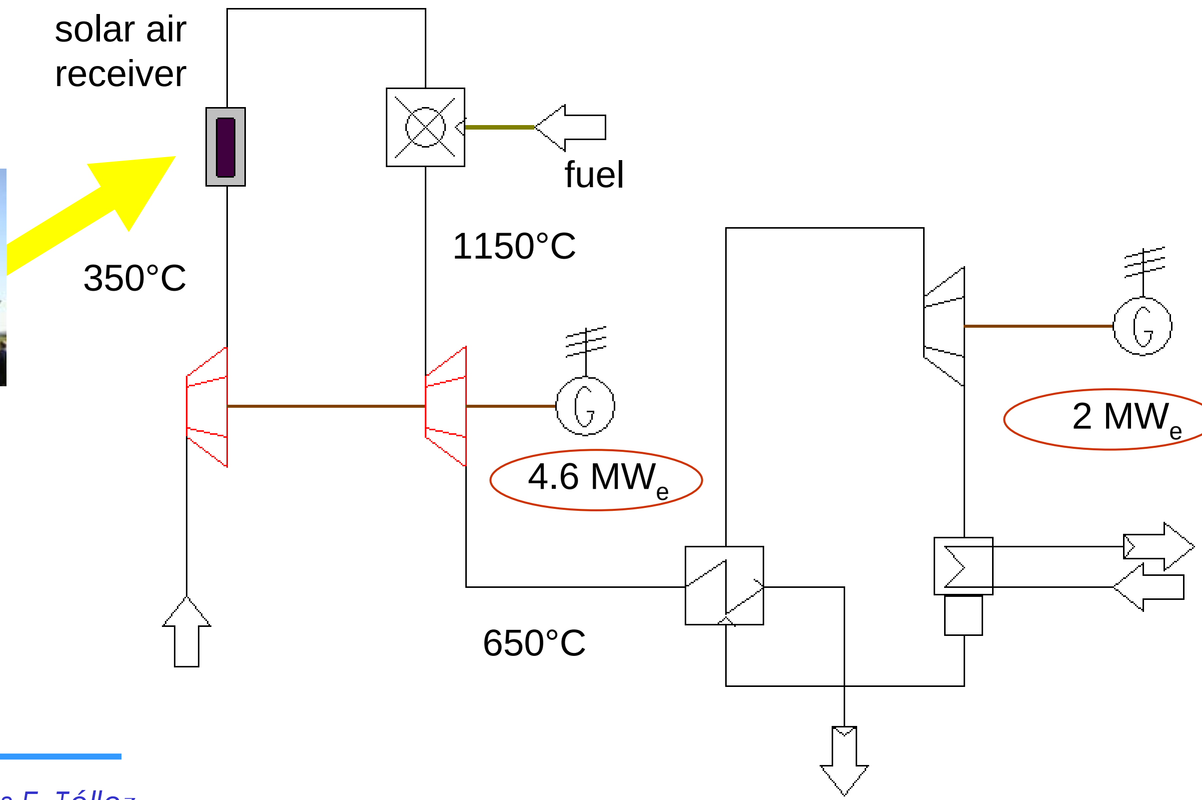




Solugas: Solar Up-scale Gas Turbine System

- Combined system
- Possibility to hybridizate with biodiesel

140 heliostats



THANKS FOR YOUR ATTENTION !

Félix M. Téllez
High Solar Concentration Technologies
www.psa.es; www.ciemat.es (felix.tellez@ciemat.es)

Felix.tellez@ciemat.es