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

- Heliostat Field
- Tower
- Receiver
- Heat Storage
- Power Block
(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
The results of investigations establishing the possibility of erecting economical solar installations in the sunny regions of the U.S.S.R., to produce $11-13 \text{T}^*/\text{hr of steam, (} \rho = 30 \text{ At, } t = 400^\circ \text{C}, \text{ are presented. The optical system of the installation consists of 1,293 mirrors of 3 \times 5 \text{ m, mounted on carriages which move on rails, positioned around a boiler-shield, on which the solar rays are focused.}$
1970’s: Odeillo solar furnace

- Built at the beginning 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.
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 Rankine, 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, …?
Learning Curve reactivated with PS10, PS20, eSolar, Gemasolar, …(reduction of ~15% has been achieved in several components –as heliostats- in the first 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).

<table>
<thead>
<tr>
<th>Project</th>
<th>Country</th>
<th>Power (MW)</th>
<th>Heat Transfer Fluid</th>
<th>Storage Media</th>
<th>Beginning operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSPS</td>
<td>Spain</td>
<td>0.5</td>
<td>Liquid Sodium</td>
<td>Sodium</td>
<td>1981</td>
</tr>
<tr>
<td>EURELIO5</td>
<td>Italy</td>
<td>1</td>
<td>Steam</td>
<td>Nitrate Salt/ Water</td>
<td>1981</td>
</tr>
<tr>
<td>SUNSHINE</td>
<td>Japan</td>
<td>1</td>
<td>Steam</td>
<td>Nitrate Salt/Water</td>
<td>1981</td>
</tr>
<tr>
<td>Solar One</td>
<td>U.S.A.</td>
<td>10</td>
<td>Steam</td>
<td>Oil/Rock</td>
<td>1982</td>
</tr>
<tr>
<td>CESA-1</td>
<td>Spain</td>
<td>1</td>
<td>Steam</td>
<td>Nitrate Salt</td>
<td>1982</td>
</tr>
<tr>
<td>MSEE/Cat B</td>
<td>U.S.A.</td>
<td>1</td>
<td>Nitrate Salt</td>
<td>Nitrate Salt</td>
<td>1983</td>
</tr>
<tr>
<td>THEMIS</td>
<td>France</td>
<td>2.5</td>
<td>Hitech Salt</td>
<td>Hitech Salt</td>
<td>1984</td>
</tr>
<tr>
<td>SFP-6</td>
<td>Russia</td>
<td>5</td>
<td>Steam</td>
<td>Water/Steam</td>
<td>1986</td>
</tr>
<tr>
<td>T3A</td>
<td>Spain</td>
<td>1</td>
<td>Air</td>
<td>Ceramic</td>
<td>1983</td>
</tr>
<tr>
<td>Solar Two</td>
<td>U.S.A.</td>
<td>10</td>
<td>Nitrate Salt</td>
<td>Nitrate Salt</td>
<td>1986</td>
</tr>
<tr>
<td>Consolar</td>
<td>Israel</td>
<td>0.5**</td>
<td>Pressurized Air</td>
<td>Fossil Hybrid</td>
<td>2001</td>
</tr>
<tr>
<td>Solgale</td>
<td>Spain</td>
<td>0.3</td>
<td>Pressurized air</td>
<td>Fossil Hybrid</td>
<td>2002</td>
</tr>
<tr>
<td>PS10+</td>
<td>Spain</td>
<td>10</td>
<td>Air/Steam</td>
<td>Ceramic</td>
<td>2008</td>
</tr>
<tr>
<td>Solar Tree+</td>
<td>Spain</td>
<td>15</td>
<td>Nitrate Salt</td>
<td>Nitrate Salt</td>
<td>2008</td>
</tr>
</tbody>
</table>

* Projects under development.
** Thermal

STE-CR. Actual Characteristics
CRS: Some key elements.
Component’s options and new Development
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.
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,...)
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
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)

- **H25**: 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. **Cylindrical 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.

Heliostats technology. Some of the latest developments of prototypes in Spain

Gemasolar new generation heliostat

(Lata, J. et al. 2010)
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 \(\rightarrow\) single optical system.

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

**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.

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

Heliostat after Canting
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.**
Ex. Options for “T” type of heliostats: Mechanical vs Hydraulic drive mechanism (f.i. heliostat Sanlucar, ...)

Heliostats - Components - Drive Mechanisms
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 establish 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 m² heliostats at PS10/20 (Abengoa)
  - 2650 X 116 m² heliostats at Gemasolar
  - 100 X 100 m² heliostats in China (Himin)
  - R&D on low-cost drives (Siemens)
  - Mass production of Az drive is needed (Sandia)
    - ~$44/m² given 2500/yr, $22/m² 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)
**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.

### Variability of Focal Image

<table>
<thead>
<tr>
<th>Error Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angulo solar (teta_s), [mrad]</td>
<td>0.009599333 radianes</td>
</tr>
<tr>
<td>Solar error (68.3% sign.), mrad</td>
<td>0.0028 radianes</td>
</tr>
<tr>
<td>Error estructura</td>
<td>0.001979899 radianes</td>
</tr>
<tr>
<td>Error seguimiento solar</td>
<td>0.002828427 radianes</td>
</tr>
<tr>
<td>Error Total (68.3% sign.)</td>
<td>0.004445222 radianes</td>
</tr>
<tr>
<td>Error Total (95% sign.)</td>
<td>0.008712635 radianes</td>
</tr>
</tbody>
</table>

### Imperfections Surface Error

- **Spherical curvature, no waviness**
- **Spherical curvature, with waviness**
Besides, the loss of efficiency of each heliostat, the solar field may be designed (choosing heliostat distribution, tower height, receiver size, ...) to obtain the optimum compromise of efficiency and costs.

\[
\eta_{\text{plant}} = \eta_{\text{solar field}} \times \eta_{\text{receiver}} \times \eta_{\text{power block}} = \frac{P_{\text{electricity}}}{P_{\text{solar incident}}}
\]

**OPTIMIZATION Process I: Optical performance**

- **COSINE EFFECT**
- **TRACKING ERROR**
- **BEAM QUALITY ERROR**
- **SPILLAGE LOSS**
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 height, 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 + …)

\[ \eta_{\text{plant}} = \eta_{\text{solar field}} \times \eta_{\text{receiver}} \times \eta_{\text{power block}} = \frac{p_{\text{electricity}}}{p_{\text{solar incident}}} \]

- **COSINE FACTOR**
- **SHADOWS + BLOCKS**
- **AIR TRANSMITTANCE**
- **SPILLAGE FACTOR**

**Figure 3: Collector Field Optical Loss Processes**
Solar Field designs & Relationship with receiver

(Receiver may be placed on Top)

North field
Circular field

Power Block
Distributed Power Towers
Multitowers
Everything is linked

Tower height increases with the power and field disposition.
The use of re-concentrators modifies the field arrangement:

Fig. 2 Modular receiver arrangement

Fig. 13 Effect of Secondary Concentrator
Towers

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

- Multiple beam-down towers to produce >20 MWₑ (Tokyo Tech)
  - Single tower 100 kWₑ demo will be operating 12/09
Solar field – receiver relationship: Concentrated solar flux distribution on aperture

Non-homogeneous flux distributions over the receiver decreases the efficiency and the life time of receiver (thermal stress)
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)
The choice of the receiver type and design may attend to several constraints and design requirements, like:

- **High absorptivity** (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.

**Tubular Receivers**

Heat transfer in series:
- Absorption
- Conduction
- Convection

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

**Tube material**
- Steel
- Ceramic
The choice of the **receiver type** and design may attend to **several constrains** and design requirements, like:

- **High absorbivity** (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.
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 storage and hybridization improve dispatchability.

- CRS as other STE technologies have a unique integrability into 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

<table>
<thead>
<tr>
<th>Options</th>
<th>CHEMICAL</th>
<th>THERMAL</th>
<th>MECHANICAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen (100 bar)</td>
<td>300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Hydrogen</td>
<td>2380</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methanol</td>
<td>4300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Natural Gas</td>
<td>5800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Oil, Gasoline</td>
<td>9000 - 11000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bituminous coal</td>
<td>12000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batteries</td>
<td>50 - 100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molten Salts</td>
<td>500 - 700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bricks / Pebbles Bed</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam (100 bar)</td>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glauber’s Salt</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotating Wheels</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pr. Air (100 bar)</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumped Storage (300 m)</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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.
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 $\Delta T$

$\text{investment cost } \sim 10-20 \$/$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 $\Delta T$
- 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:

<table>
<thead>
<tr>
<th>Operating Temperature</th>
<th>Direct Steam Generation</th>
<th>(Nitrate) Molten Salts</th>
<th>Atmospheric &amp; Presurized Air</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 290º C Saturated</td>
<td>565 ºC</td>
<td>750-900ºC</td>
</tr>
<tr>
<td></td>
<td>290-550 ºC Superheated</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>550-650 ºC Supercritic</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermodynamic Cycle</th>
<th>Rankine (or integration as preheating in CC)</th>
<th>Rankine (or integration as preheating in CC)</th>
<th>Rankine / Brayton (or integration in top of CC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Availability of Heat storage</th>
<th>¿! Presurized steam vessel ~ 30 mintos</th>
<th>Yes Two tanks (hot/cold) ~15 h</th>
<th>Yes Pebbles Beds (termocline) ~3 h</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Capacity Factor (full load equivalent)</th>
<th>2.200 h/year</th>
<th>2200 - 5.700 h/year</th>
<th>3.500 h/year</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Overall Annual Efficiency</th>
<th>13-16 %</th>
<th>14-18 %</th>
<th>14-18 %</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Estimated cost of electricity</th>
<th>0,17-0,23 €/kWh-a</th>
<th>0,14-0,17 €/kWh-a</th>
<th>0,13-0,16 €/kWh-a</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Commercial Situation (actuales / potenciales)</th>
<th>PS10, PS20 (Saturado), eSolar (Sobrec.) Brightsource E (Supercrit.)</th>
<th>Gemasolar/Solar Tres Rockydyne /SolarReserve Abu-Dhabi?</th>
<th>(1ª versión PS10)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Pending ¡!</th>
<th></th>
<th></th>
</tr>
</thead>
</table>
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 expensive materials (due to higher temperatures)
State of the art

- Resurrection of steam receiver technology
  - PS-10 MW₀ on grid 6/07, PS-20 5/09 (Abengoa)
  - 5 MW₀, 2-tower plant on utility grid 7/09 (eSolar)
  - 5 MWₜ thermal-only demonstration since late 08 (Brightsource)
  - Lessons learned from 10 MW₀ Solar One, shutdown in 1988
  - Steam receivers perceived as “low risk,” many PPA’s announced
Steam Receivers

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

- 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 scheme

- 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 up to 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

24-03-08

Operación (7h a potencia nominal)
Desenfoque Automático de Heliostatos
por Plena Potencia en Sistemas

Arranque

Hora Local

Potencia Turbina [MWe]
Alm. acumulado [MWhe]

Irradiancia [kW/m²]
Nº Real heliostatos/1000

Potencia Térmica a Almacenamiento [MWe]

Precalentamiento

Precautelamiento

6:00 7:48 9:36 13:12 15:00 16:48 18:36 20:24

Almacenamiento real acumulado (MWhe)
Almacenamiento real (MWt)
Nº Real heliostatos/1000

Potencia real de la TV (MWe)
Irradiancia (kW/m²)
PS10. Operation in a day requiring support with gas

07-11-08

<table>
<thead>
<tr>
<th>Time (Local)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5:16</td>
</tr>
<tr>
<td>6:04</td>
</tr>
<tr>
<td>6:52</td>
</tr>
<tr>
<td>7:40</td>
</tr>
<tr>
<td>8:28</td>
</tr>
<tr>
<td>9:16</td>
</tr>
<tr>
<td>10:04</td>
</tr>
<tr>
<td>10:40</td>
</tr>
<tr>
<td>11:28</td>
</tr>
<tr>
<td>12:16</td>
</tr>
<tr>
<td>13:04</td>
</tr>
<tr>
<td>13:52</td>
</tr>
<tr>
<td>14:40</td>
</tr>
<tr>
<td>15:28</td>
</tr>
<tr>
<td>16:16</td>
</tr>
<tr>
<td>17:04</td>
</tr>
<tr>
<td>17:52</td>
</tr>
<tr>
<td>18:40</td>
</tr>
</tbody>
</table>

Key:
- Teal: Power real from the TV (MWe)
- Blue: Accumulated energy (MWhe)
- Orange: Thermal power and storage (MWh)
- Red: Natural Gas Consumption (MWe)
- Green: Irradiance (kW/m²)
- Purple: Real heliostats/1000

Y-axis (left): Power Turbine [MWe]
Y-axis (right): Radiation [kW/m²]
X-axis: Local Time
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%.
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 Sun Tower**
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

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Aspen SunTower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country</td>
<td>United States</td>
</tr>
<tr>
<td>Location</td>
<td>Lancaster, California (Antelope Valley)</td>
</tr>
<tr>
<td>Owner(s)</td>
<td>eSolar</td>
</tr>
<tr>
<td>Technology</td>
<td>Power tower</td>
</tr>
<tr>
<td>Turbine Capacity</td>
<td>92.0 MW</td>
</tr>
<tr>
<td>Status</td>
<td>Under development</td>
</tr>
<tr>
<td>Start Year</td>
<td>2012</td>
</tr>
</tbody>
</table>

**Do you have more information, corrections, or comments?**

<table>
<thead>
<tr>
<th>Status Date</th>
<th>November 6, 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td></td>
</tr>
<tr>
<td>Technology</td>
<td>Power tower</td>
</tr>
<tr>
<td>Status</td>
<td>Under development</td>
</tr>
<tr>
<td>Country</td>
<td>United States</td>
</tr>
<tr>
<td>City</td>
<td>Lancaster</td>
</tr>
<tr>
<td>State</td>
<td>California</td>
</tr>
<tr>
<td>Region</td>
<td>Antelope Valley</td>
</tr>
<tr>
<td>Electricity Generation</td>
<td>192,000 MWh/yr</td>
</tr>
<tr>
<td>Start Production</td>
<td>2012</td>
</tr>
<tr>
<td>PPA/Tariff Date</td>
<td>June 25, 2009</td>
</tr>
</tbody>
</table>

**Participants**

<table>
<thead>
<tr>
<th>Developer(s):</th>
<th>NRG Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation Offtaker(s):</td>
<td>Pacific Gas &amp; Electric (PG&amp;E)</td>
</tr>
</tbody>
</table>

**Plant Configuration**

<table>
<thead>
<tr>
<th>Solar Field</th>
<th>eSolar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Block</td>
<td>Turbine Capacity (Net): 92.0 MW</td>
</tr>
</tbody>
</table>

---

**STE with Central Receiver Systems F. Téllez**

---

Slide 58
Ivanpah: 440 MWe (by Brightsource ~Luz2) in California (superheated steam)

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

### Background
- **Power tower**
- **California**
- **San Bernardino, CA**
- **35°33' 8.5'' North, 115°27' 30.57'' West**
- **4,073 acres**
- **2,717 kWh/m²/yr**
- **1,075,232 MWh/yr (Expected/Planned)**
- **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: 2,295,950 m²
    - # of Heliostats: 214,000
    - Heliostat Aperture Area: 14.08 m²
    - Tower Height: 459 ft

---

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

### 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
- **Cooling Method**: Dry cooling
- **Efficiency (Gross)**: 28.72%
- **Fossil Backup Type**: Natural gas

---

*Do you have more information, corrections, or comments?*
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 °C
- 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, ...)

**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
Receptor cavidad con 16 m² apertura

Temperatura sales = 250/450°C

Vapor 410°C y 40 bar

Central Themis en Targasonne (Francia)

Potencia: 2,5 MWe

201 helióstatos y 10.740 m²

Torre 106 m
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** 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 Technology Promoters: Solar Reserve/Rocketdyne (USA))
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
Open Volumetric Air Receiver (formerly PHOEBUS)

Achievable Steam Parameters:
- 700°C
- 160 bar

Primary Heat Transfer Medium: Air

Backup Options:
- Thermal Storage
- Duct Burners

Backup Fuels:
- Natural Gas
- Fuel Oil

Technology Status:
- Successful 3 MW Thermal System
- Demonstration at Plataforma Solar

Turnkey System Supplier:
- Kraftanlagen München

System Components:
- Receiver
- Cold Air 110°C
- Hot Air 680°C
- Steam 65 bar, 460°C
- Steam Generator
- Power Block
- Blower
Experimental Plant Julich (open volumetric)

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

ICIERP

[Image of solar tower and schematic diagram]
CRS with (pressurized) Air
SRC- Pressurized Air

Aimed for Solar Combined cycle

Project “Solgate”
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 hybridize with biodiesel

140 heliostats

Solar air receiver

800°C

1150°C

4.6 MWₑ

650°C

2 MWₑ
THANKS FOR YOUR ATTENTION!

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