Instituto Superior Técnico
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Harnessing the Sun:

# Concentrated Solar Power

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# CSP - A very old idea…

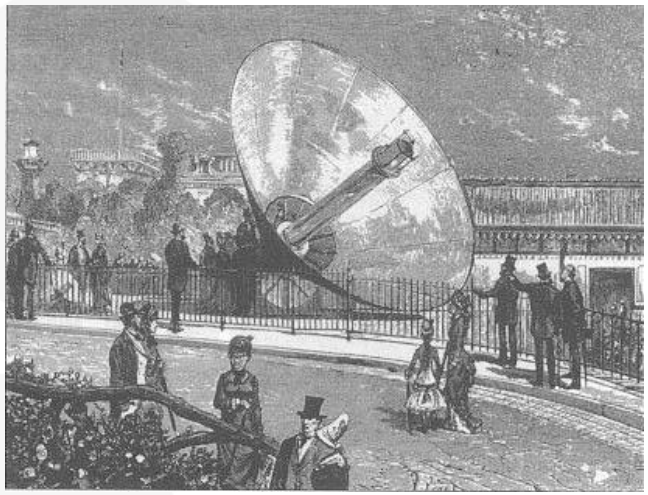
➢**214-212 BC, Syracuse** – Archimedes uses “burning glass” to concentrate sun rays onto invading Roman ships.

# CSP - A very old idea…

- **20 AD, China –** Chinese document the use of burning mirrors to light torches for religious purposes

- **1767, Switzerland –** Swiss scientist Horace de Saussure is credited with building the world's first solar collector (actually a solar oven)

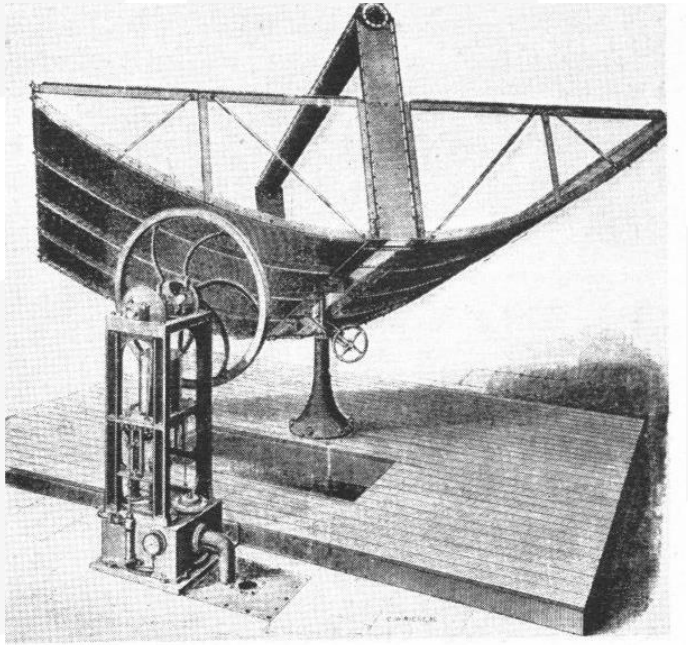
- **1866, France –** August Mouchet builds the first solar steam engine, using a parabolic trough to produce steam



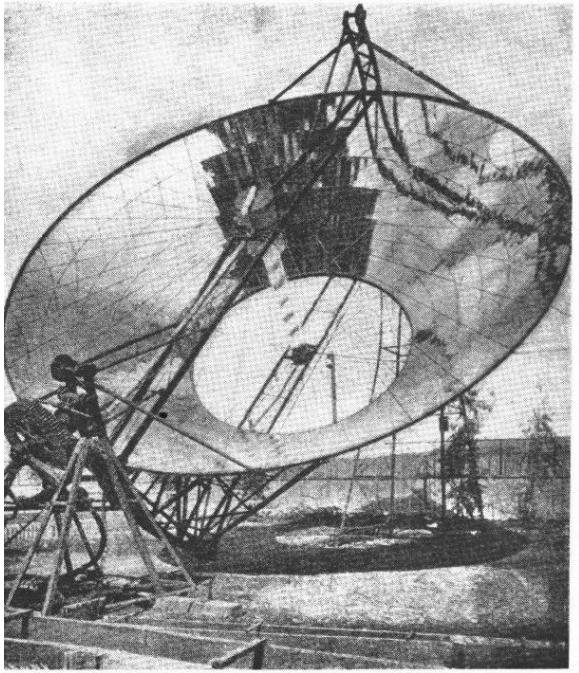
# CSP - A very old idea…

➢**1886, Italy –** Alessandro Battaglia obtains the first patent for a solar collector

➢ Over the following years several inventors develop CSP systems for irrigation, refrigeration, locomotion, etc.



A SUN-POWER PLANT OF 1883.
The boiler had a diameter of 6¼ inches and was 11 feet long. 163 square feet of sunshine were collected.



THE PASADENA SUN-POWER PLANT OF 1901.
Maximum diameter, 33 feet 6 inches. The boiler had a capacity of 83½ gallons. Maximum output, 4½ horse-power. 150 square feet of radiation were required per horse-power.

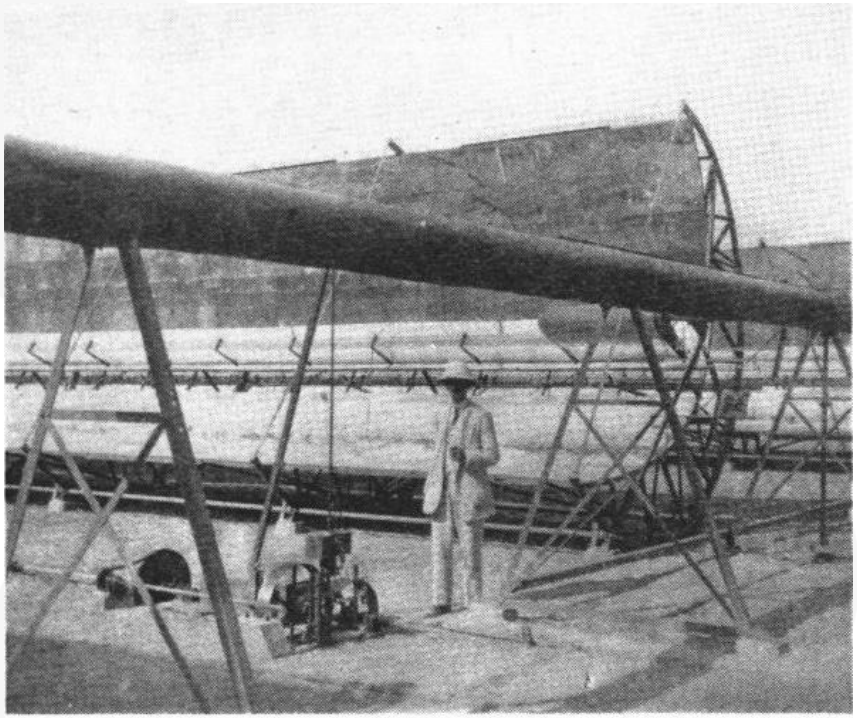
# CSP - A very old idea…

➢**1902, Portugal –** Padre Manuel António Gomes (Padre Himalaya) build his second CSP device achieving temperatures of 2000ºC, melting a large basalt block

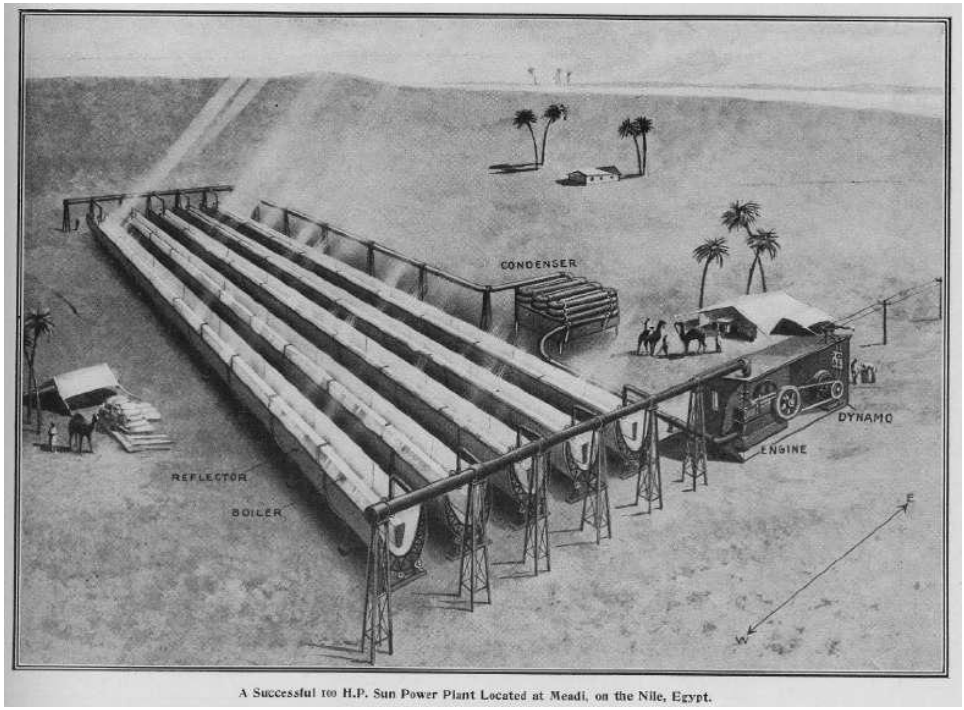
➢**1904, EUA -** Padre Himalaya presents his third CSP device the *Pirelióforo* at the Saint Louis Universal Exposition achieving 3800ºC and wining the Grand Prize of the Louisiana Purchase Exposition.

# CSP - A very old idea…

➢**1913, Egypt –** Parabolic solar collectors were used to drive a steam water pumping system in a small farming community



THE SHUMAN-BOYS SUN-POWER PLANT AT MEADI, EGYPT, 1913.




A Successful 100 H.P. Sun Power Plant Located at Meadi, on the Nile, Egypt.

# CSP – First generation

➢**1968, Italy –** Giovanni Francia builds the first operational CSP plant. It consists of a central receiver surrounded by a heliostat field

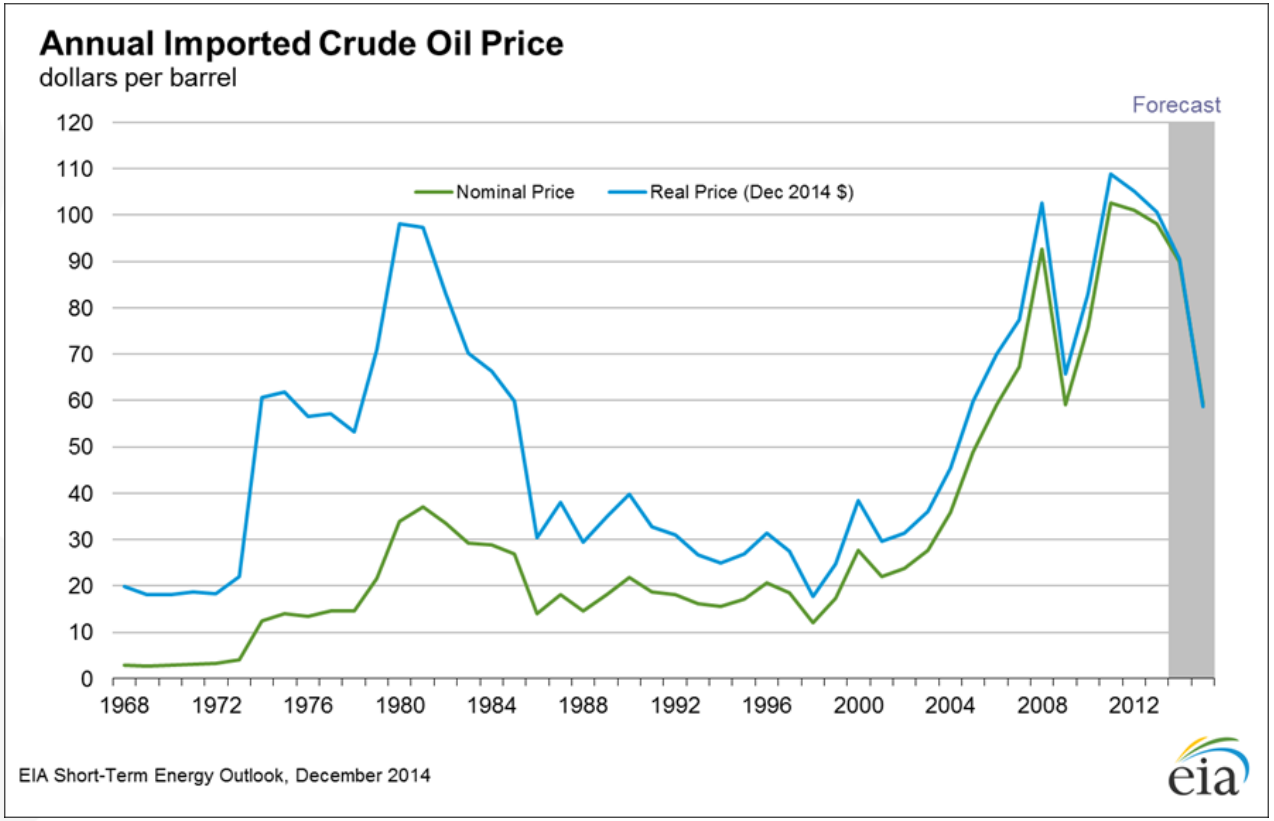
➢ **1970's** – The 1973 and 1979 oil crisis drive the need for new energy, sources spurring R&D in renewable energies. As a consequence solar thermal technologies' development flourish

➢**1980's** – First commercial exploration of CSP technologies for electricity production: The Solar Electricity Generating Systems

➢ Total capacity of 354 MW is installed in nine CSP plants between 1984 and 1990

# CSP – Generation gap

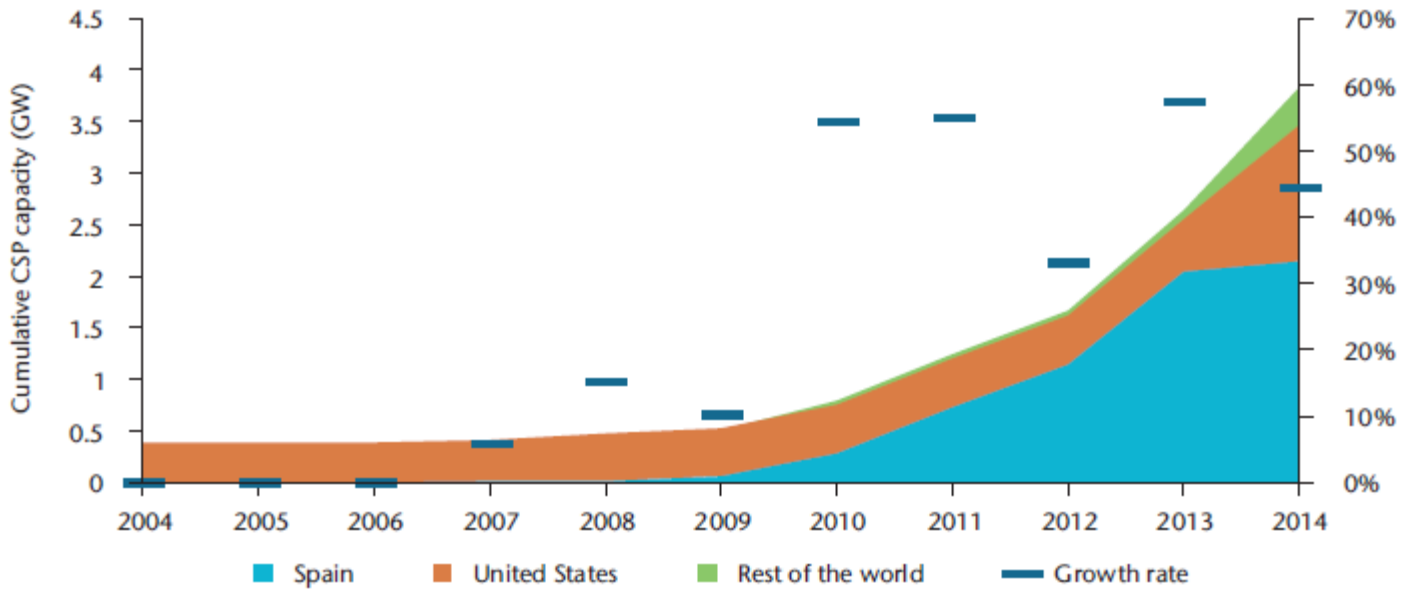
- And suddenly almost all stopped…



# CSP – Generation gap

- R&D centers kept working on CSP while the SEGS and Solar One and Two plants demonstrated the long term feasibility of the technology

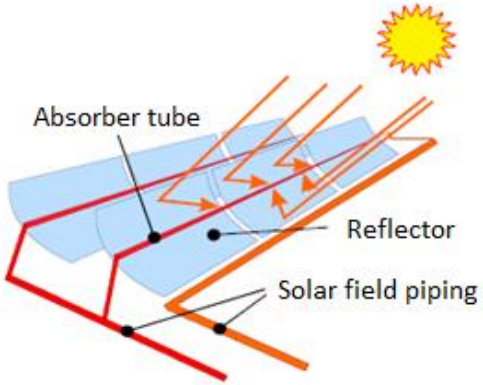
- When the next shock arrived CSP was ready for deployment



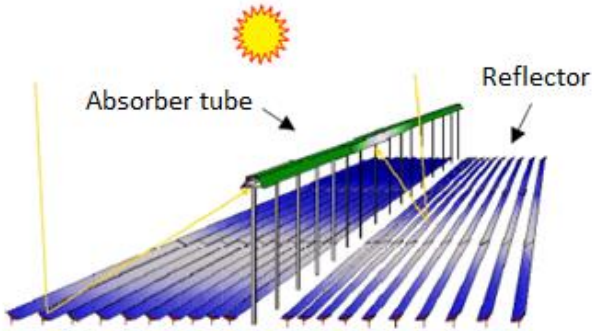

Source: IEA Technology Roadmap STE, 2014

# Concentrated Solar Power Plants

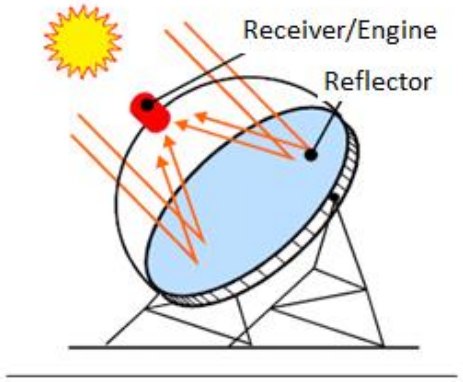
The technologies



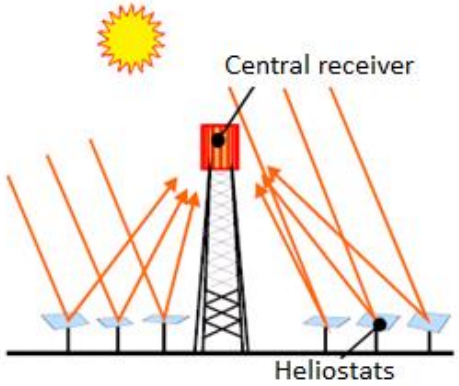

Parabolic trough




Linear Fresnel



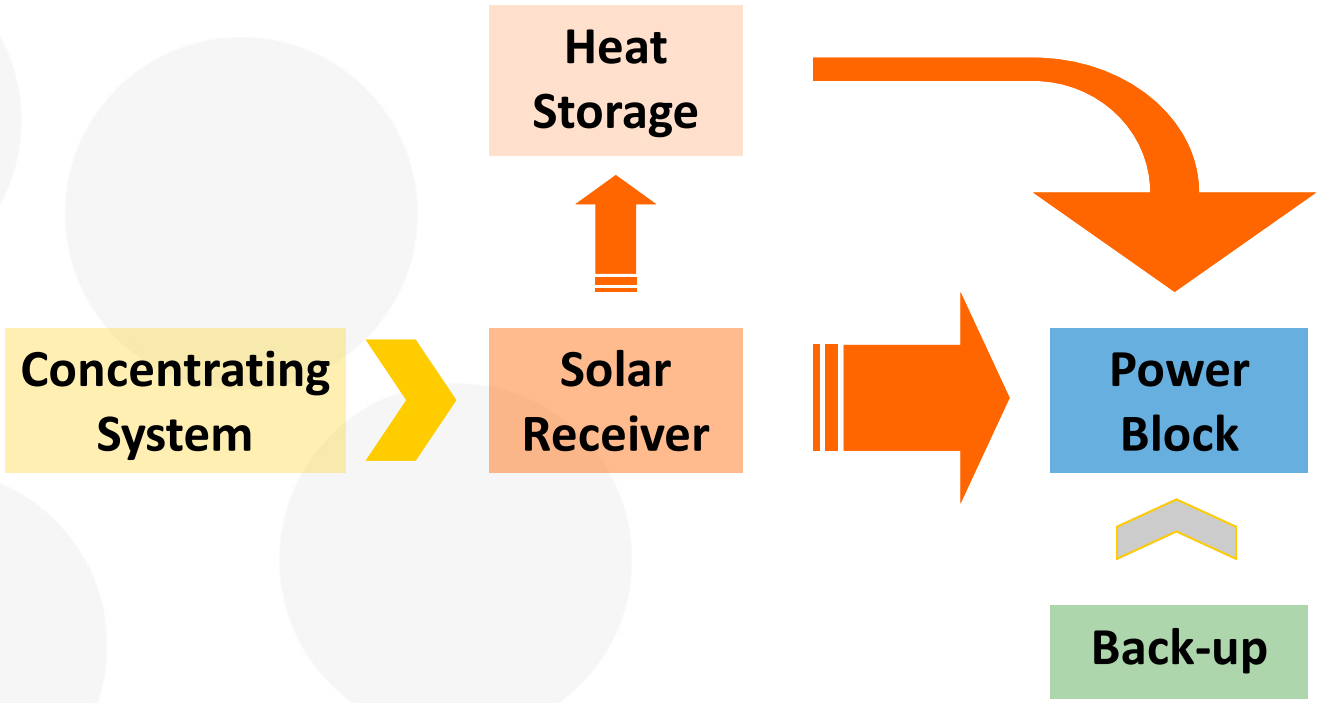

Parabolic dish



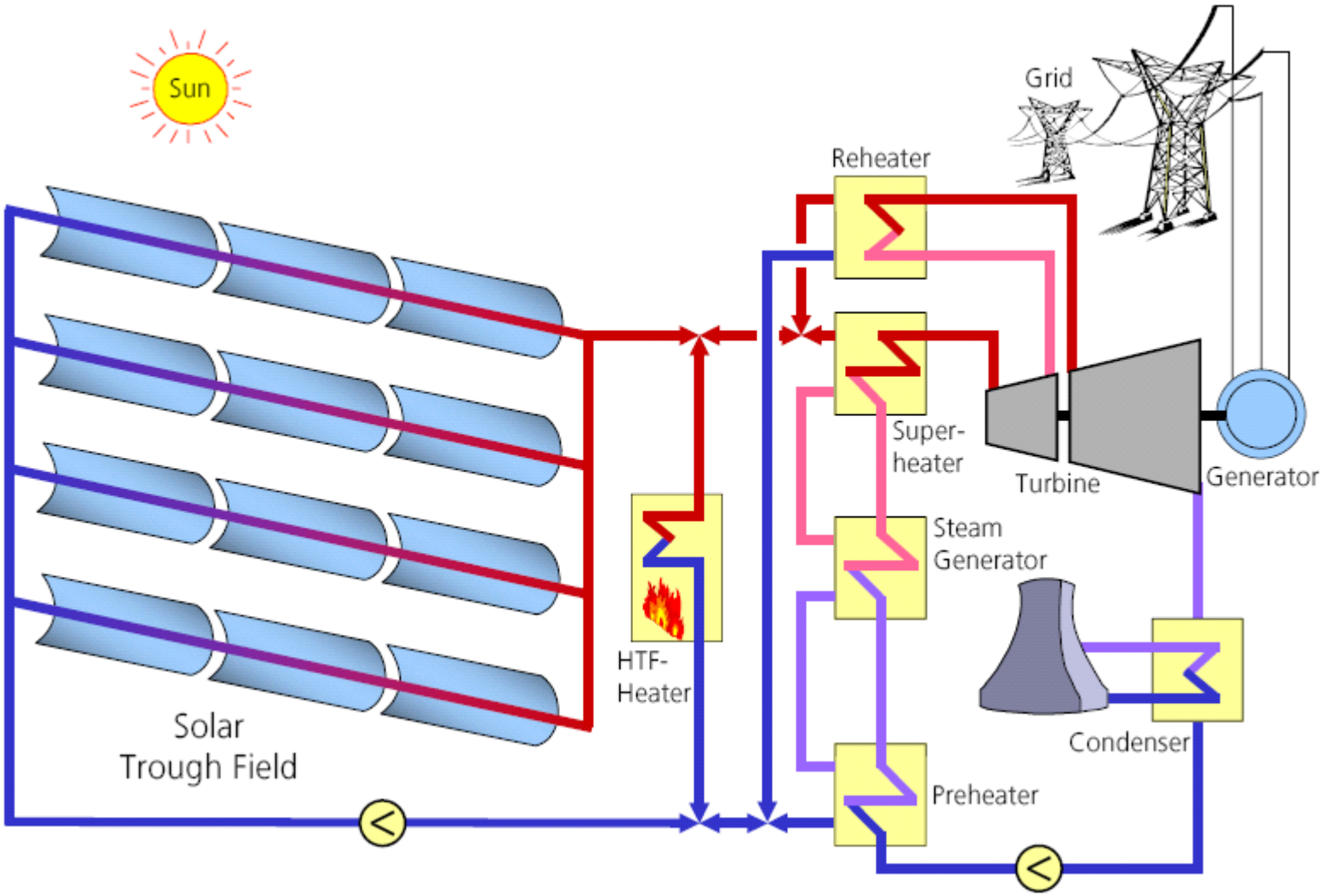

Solar tower

Source: Desertec

# Working Principle (for STE)



# Parabolic trough plants



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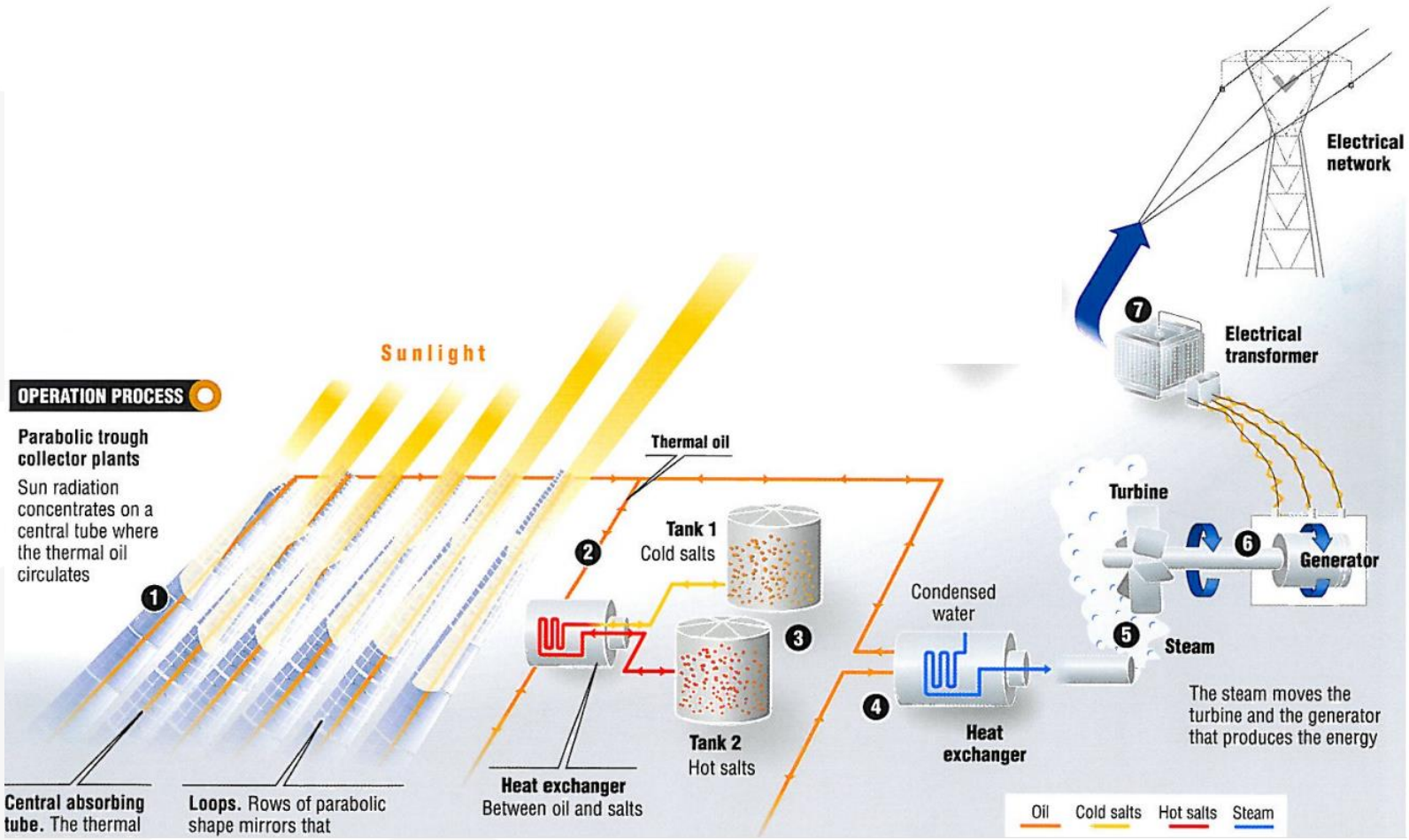


Source: Torresol Energy

# Parabolic trough plants

- Single axis tracking
- Absorber located in evacuated tube
- Operation temperature:
  - Synthetic oil as HTF - up to 390ºC
  - Molten salt as HTF – up to 550ºC
- Typical concentration factor: 70 - 80 suns
- Maximum efficiency: 14 - 21% (solar to electricity)
- Annual efficiency: 11 - 16% (solar to electricity)
- Capacity Factor: 25-28% (no TES) or 29-43% (7h TES)

Sources: Abengoa; Kuravi et al., Progress in Energy and Combustion Science, 2013

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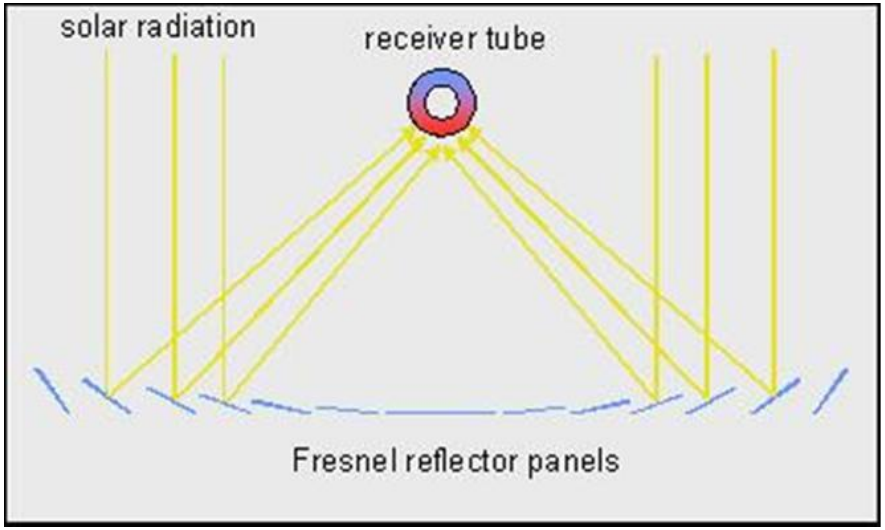
# Linear Fresnel plants

**Idea: Approximate the parabola by flat mirrors tangent to a parabolic curve**

Source: Solarmundo

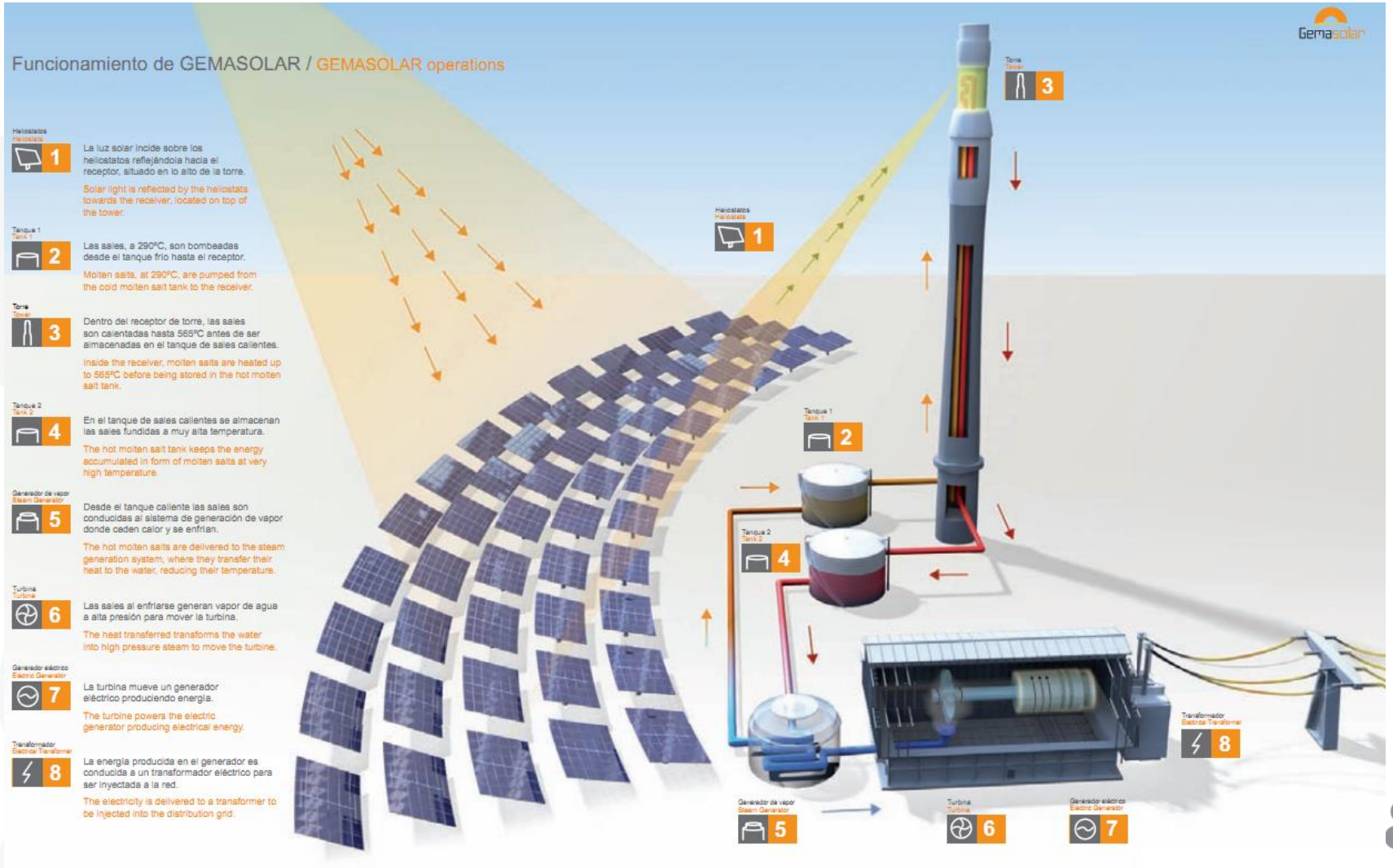


# Linear Fresnel plants

- Single axis tracking
- Less absorber per m2 --> lower thermal losses
- Fixed absorber: lower costs and easier O&M
- Operation temperature < 390 ºC
- Typical concentration factor: >60 suns
- Maximum efficiency: ~18 % (solar to electricity)
- Annual efficiency: ~13 % (solar to electricity)
- Capacity Factor: 22-24 % (no TES)

**1MWth - Liddell Coal Power Station, Australia**

# Central tower receiver




Source: Torresol Energy

# Central tower receiver

- Double axis tracking
- Absorber located in central tower
- Operation temperature: 250 - 1000 ºC
- Typical concentration factor: 200 - 1000 suns (can be higher)
- Maximum efficiency: 23 – 35% (solar to electricity)
- Annual efficiency: 7 - 20% (solar to electricity)
- Capacity Factor: 27% (no TES) or 55% (10h TES)

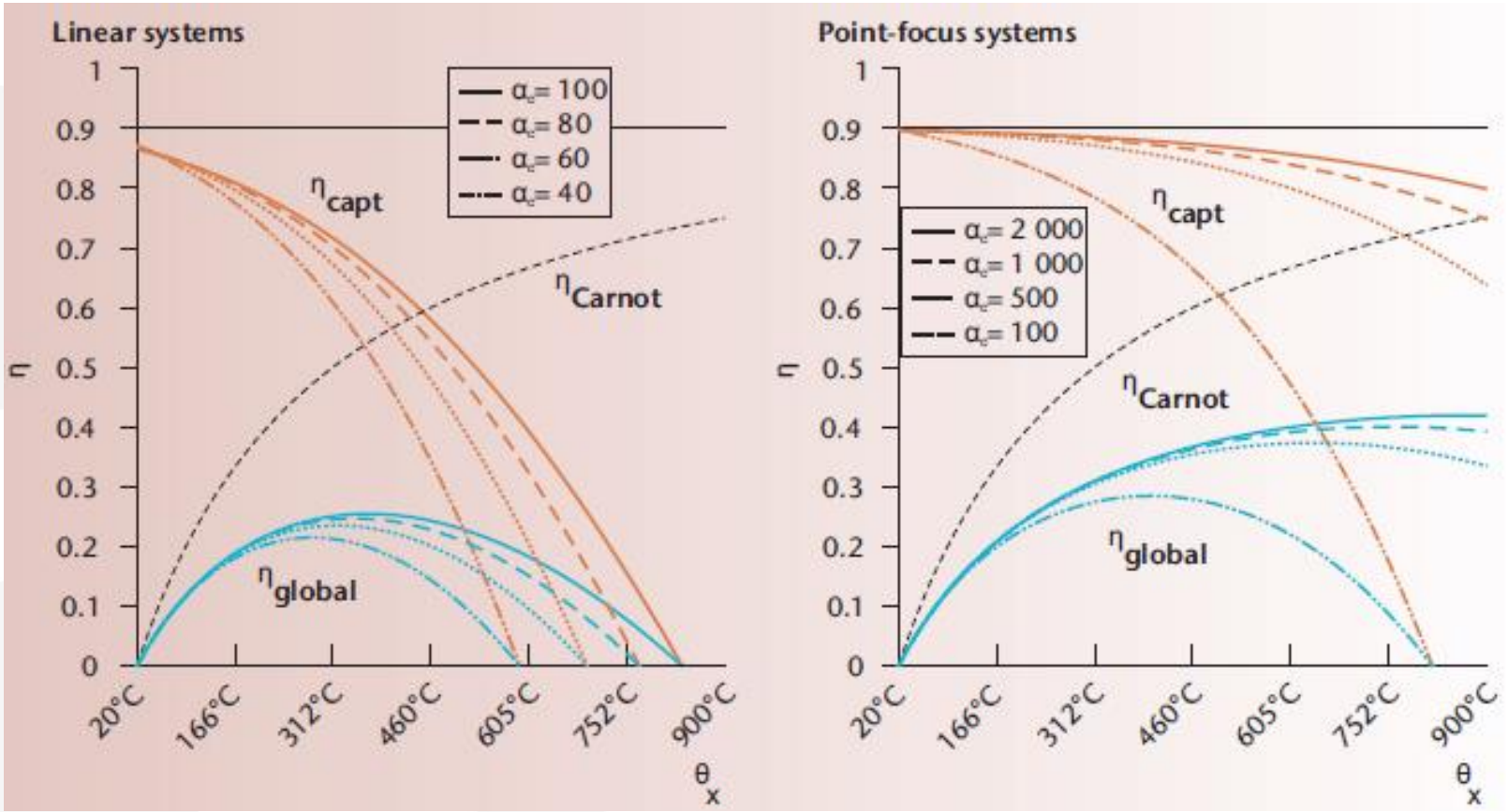
Sources: Torresol Energy; PSA; Kuravi et al., Progress in Energy and Combustion Science, 2013

# Parabolic dish

- Double axis tracking
- Absorber located in parabola focus
- Operation temperature: 550 - 750 ºC
- Typical concentration factor: > 1300 suns
- Maximum efficiency: 20 - 30% (solar to electricity)
- Annual efficiency: 12 - 25% (solar to electricity)
- Capacity Factor: 25-28%

Source: Infinia, Kuravi et al., Progress in Energy and Combustion Science, 2013

# Performance




Source: IEA Technology Roadmap STE, 2014

# Performance

| CSP technology | Peak solar to electricity conversion efficiency (%) | Annual solar-to-electricity efficiency (%) | Water consumption, for wet/dry cooling ($m^3$/MWh) |
|---|---|---|---|
| Parabolic troughs | 23–27 | 15–16 | 3–4/0.2 |
| Linear Fresnel systems | 18–22 | 8–10 | 3–4/0.2 |
| Towers (central receiver systems) | 20–27 | 15–17 | 3–4/0.2 |
| Parabolic dishes | 20–30 | 20–25 | <0.1 |

Source: EASAC

- Unique capacity for hybridization
- TES or back-up ensure dispatchability
- Can supply base, intermediate and peak load
- Ability to supply Summer peak load, when water and wind are scarcer
- Aplications ranging from kW to hundred MW scale

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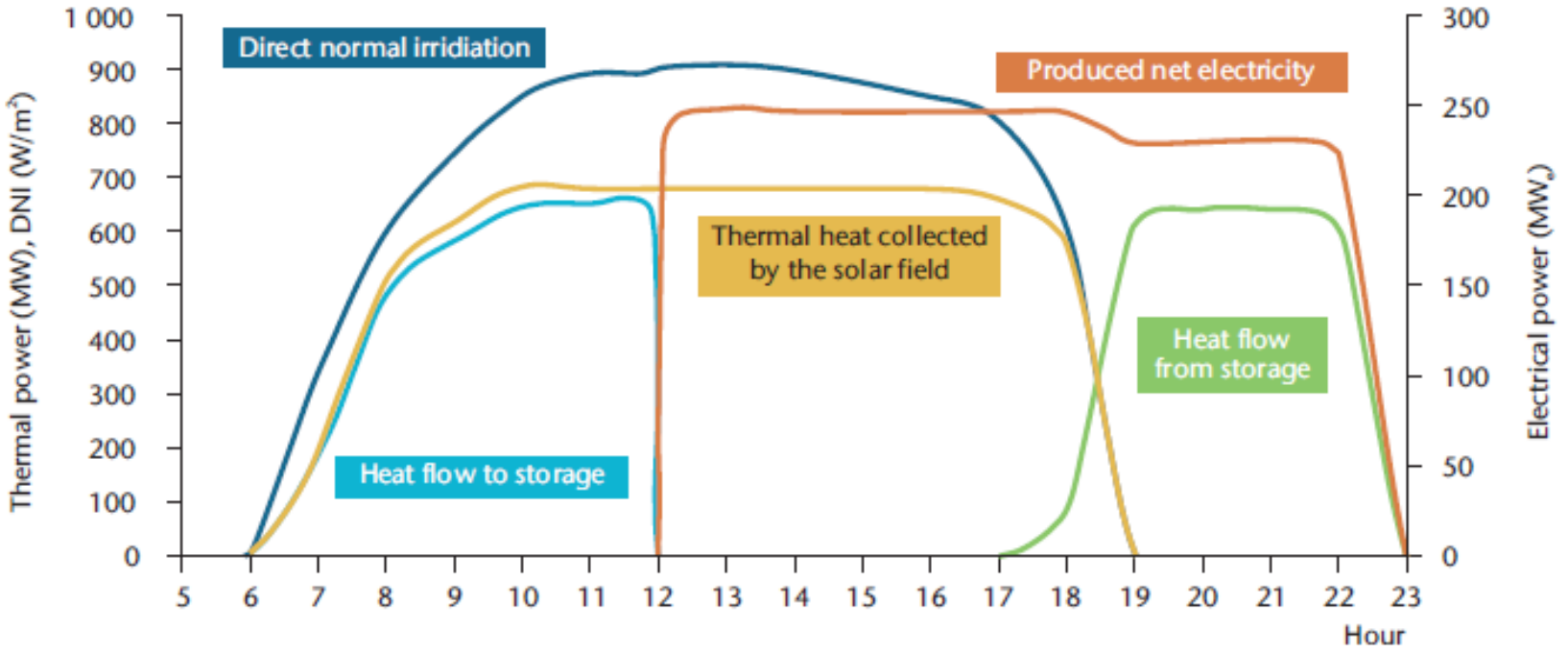
# Thermal Energy Storage




Notes: the graph shows on left scale the DNIR and the flows of thermal exchanges between solar field, storage and power block, and on the right scale electricity generation of a 250-MW (net) CSP plant with storage. Courtesy of ACS Cobra.

Source: IEA Technology Roadmap STE, 2014

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# Thermal Energy Storage

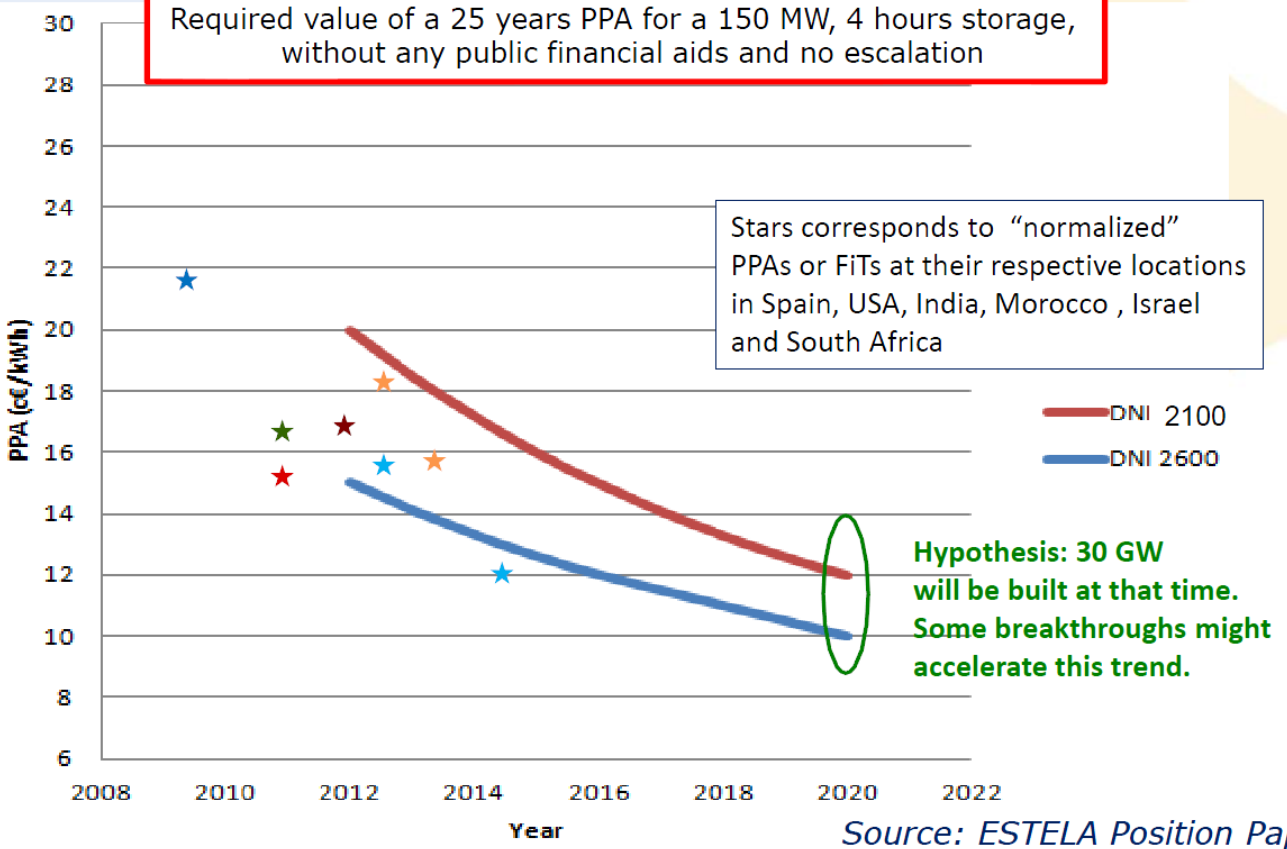
| Design concept | Heat storage media | Heat transfer fluid |
|---|---|---|
| | **Sensible Heat Storage** | |
| Two-tank: *i) direct, ii) indirect* | Molten salts | Mineral oil |
| Single-tank: *i) thermocline, ii) stratifying TES/integrated steam generation* | Inert filler solids | Molten salts |
| | Concrete | Steam |
| Special block for solid materials | Solids/particles | Gas ($CO_2$, air, helium, etc.) |
| | **Latent Heat Storage** | |
| Special equipment for PCMs | Phase-change materials (PCMs) | Steam |
| | **Chemical Storage** | |
| Special equipment for thermo- chemical products | Thermo-chemical products or solutions | Various |

| Storage concept/material | Storage capacity (kWh/m³) | Actual cost (€/kWh) | Cost expectation (€/kWh) |
|---|---|---|---|
| Sensible: liquid (depending on $\Delta T$) | 30–90 | 30–70 | 20–50 |
| Sensible: solid (depending on $\Delta T$) | 20–100 | 30–50 | 15–30 |
| Phase-change materials | 50–150 | 80–120 | 30–50 |
| Thermo-chemical reactions | 250–400 | n.a. | 10–50 |

Source: EASAC

# What about costs?

## Cost reduction estimations: The view from the Industry




*Source: ESTELA Position Paper*

# Future prespectives

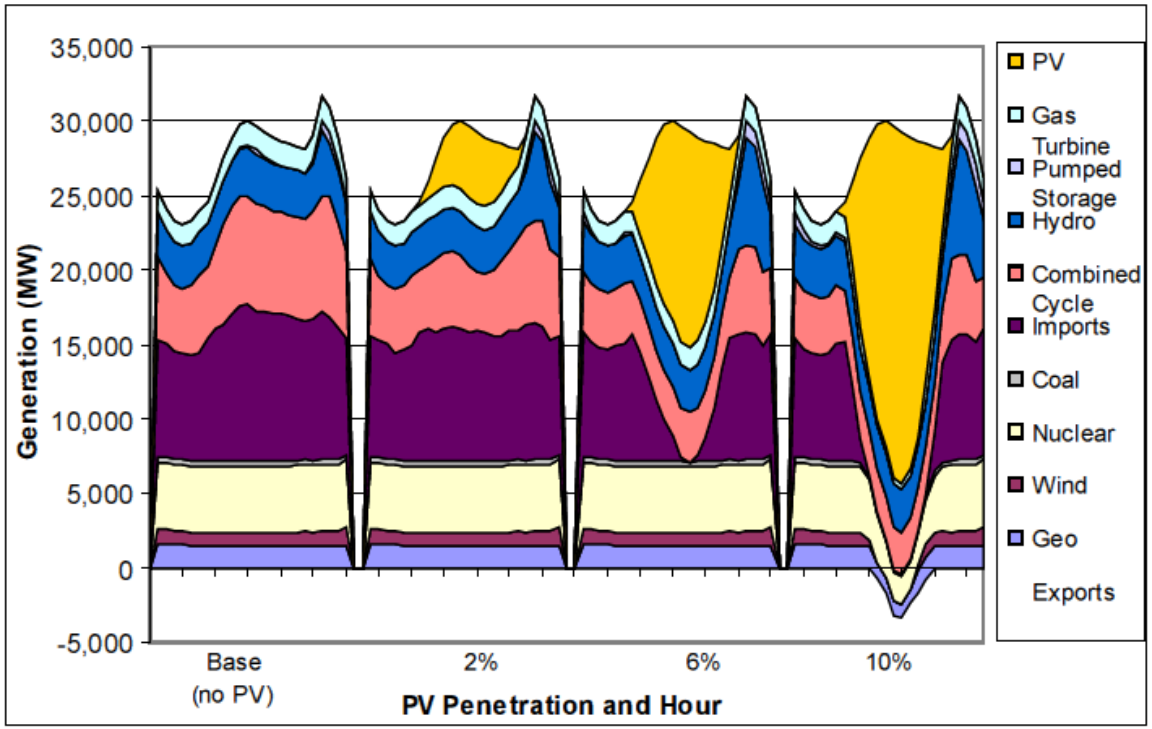
## Breaking News

- ✓ The requested PPAs for the two new STE plants in Morocco (200 MW PT & 150 MW T) were in the range of 12c€/kWh


- ✓ The IEA foresees 11% of STE contribution to the world electricity generation by 2050
- ✓ In the Middle East and Africa STE will be the dominant technology by 2050 while in the USA STE and PV will play a similar role.
- ✓ The STE installed power by 2050 would be 1.000 GW.

# Problems integrating renewables

- Consumption and renewable resource availability may differ – resource variability
- Limited flexibility from conventional generators




**Simulated dispatch in California for a spring day with PV penetration from 0%–10%**

Source: Denholm and Mehos, NREL 2011

# Problems integrating renewables

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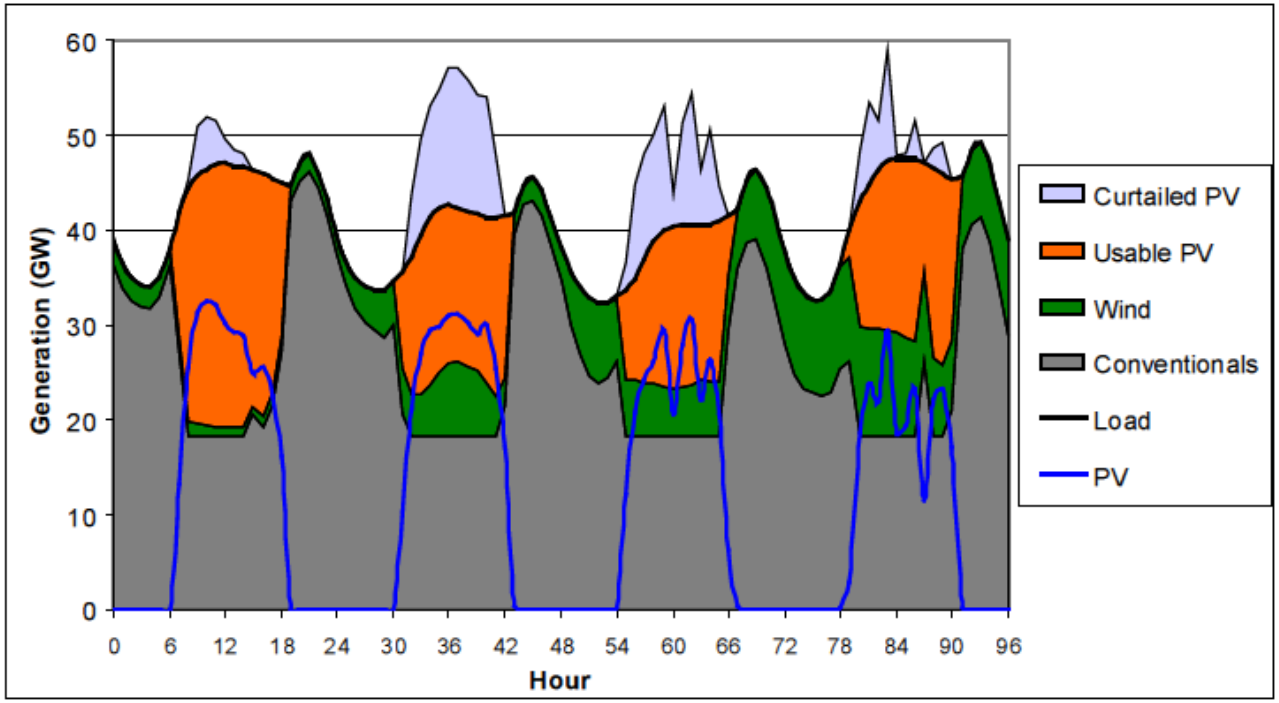
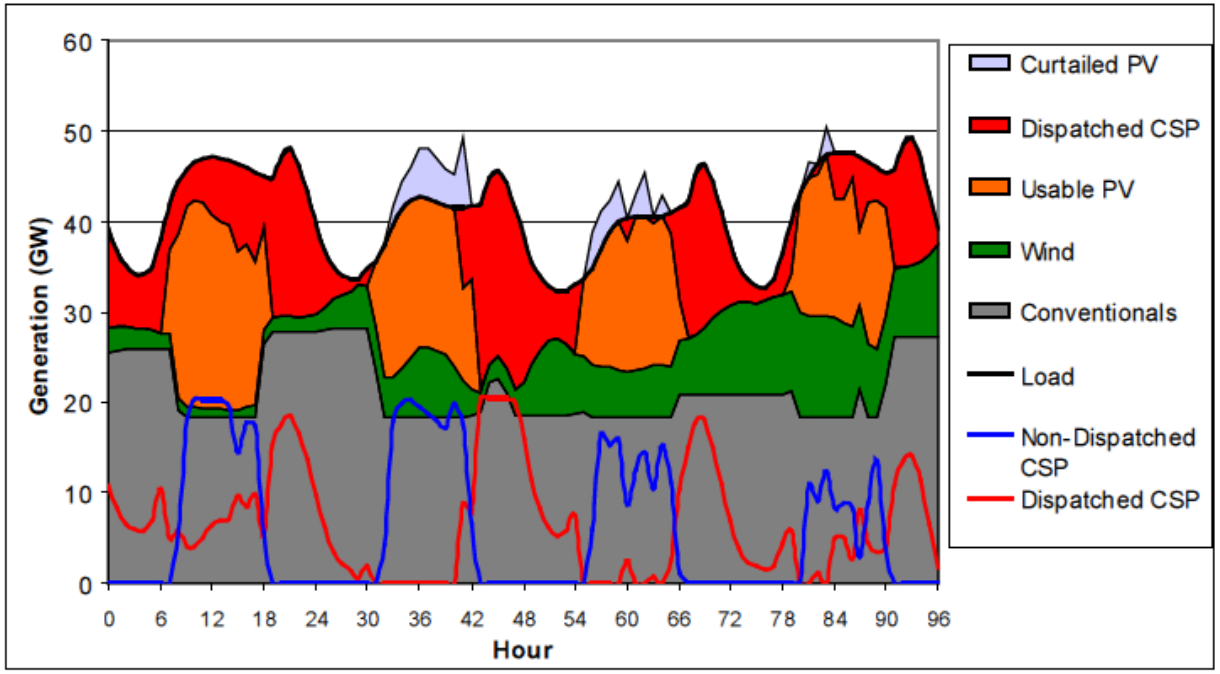



**Simulated system dispatch on April 7-10 with 20% contribution from PV generation and resulting curtailment due to grid flexibility constraints**

Source: Denholm and Mehos, NREL 2011

# Solution: CSP+TES ?!

- TES turns CSP into a dispatchable technology
- Increases grid flexibility
- Increases renewable energy sustainable grid penetration




**Simulated system dispatch on April 7-10 with 15% contribution from PV and 10% from dispatchable CSP**

Source: Denholm and Mehos, NREL 2011

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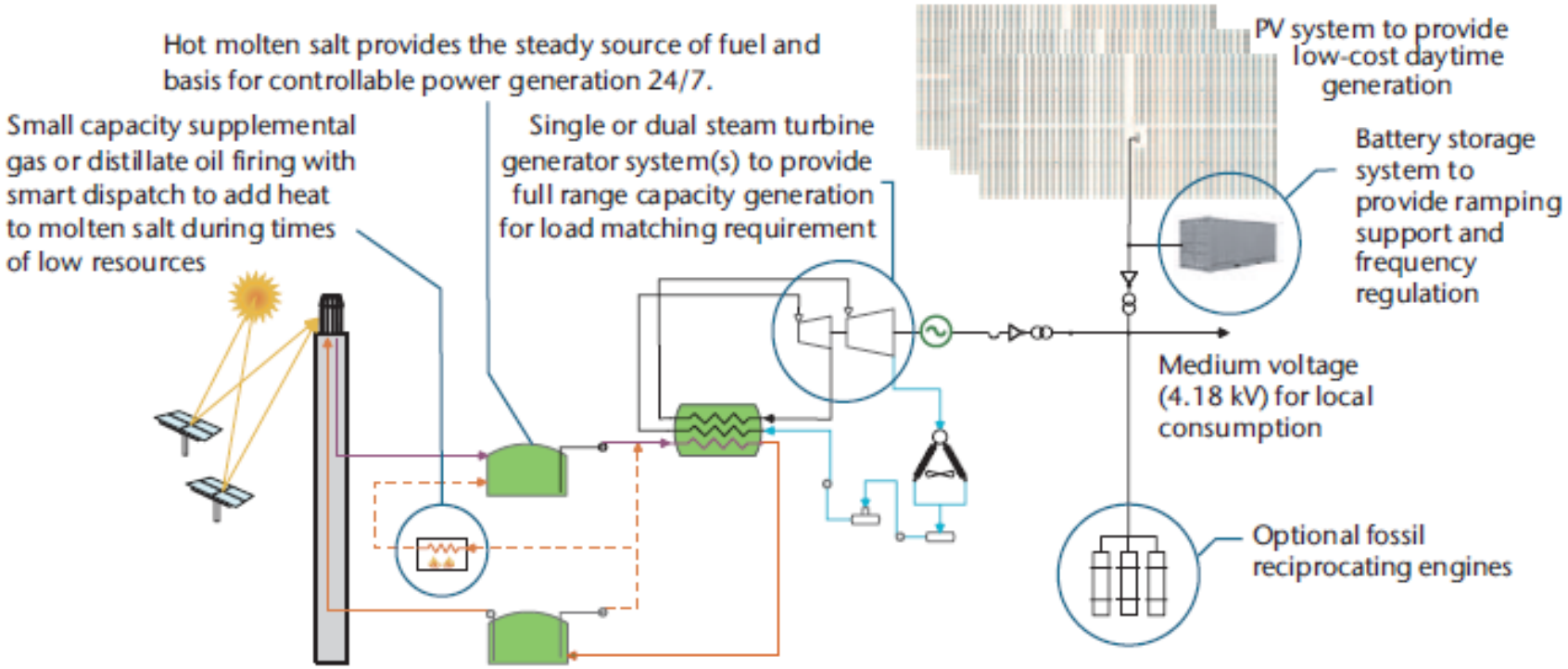
# STE +PV




Source: Gould, W. (2014), *SolarReserve, Brief Status and R&D Directions*, presentation at the IEA workshop on solar electricity roadmaps, Paris, 3 February.

- STE nd PV can be combined in a single offer

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# Thank you for your attention!

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