SFERA-III

Solar Facilities for the European Research Area

1st Summer School "Thermal energy storage systems, solar fields and new cycles for future CSP plants"
WP1 Capacity building and training activities
Odeillo, France, September 9th-11th 2019

"TES for solar thermal power plants : Introduction, Commercial systems, Integration issues & Latent heat"

Eduardo Zarza, Esther Rojas, CIEMAT-PSA (Spain)

NETWORKING

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Solar Facilities for the European Research Area

SFERA-III
1st Summer School
September, 9th- 10th, 2019
CNRS- PROMES, Odeillo, France

TES for solar thermal power plants

Introduction, Commercial systems,

Integration issues and Latent heat

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Contents

- Introduction
- Commercial systems →Sensible heat storage
- Latent heat storage → Integration Issues

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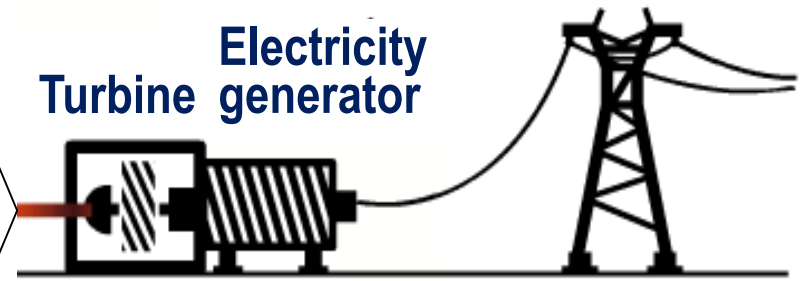
Electricity generation from thermal power

- **Fossil** (gas&coal)
- **Nuclear**
- **Renewables**
  - biomas
  - solar-thermal
  - geothermal

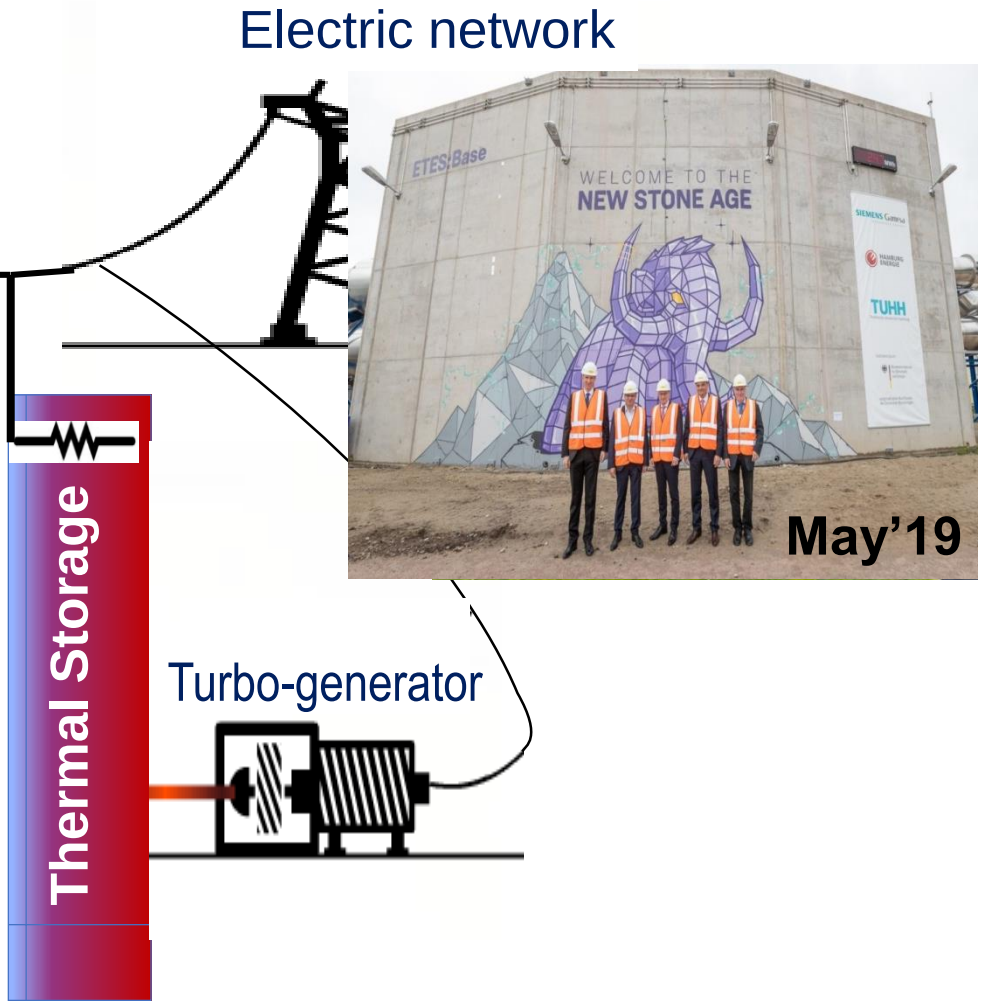
Thermal Storage

Thermal Energy
(steam, gas,T,P)



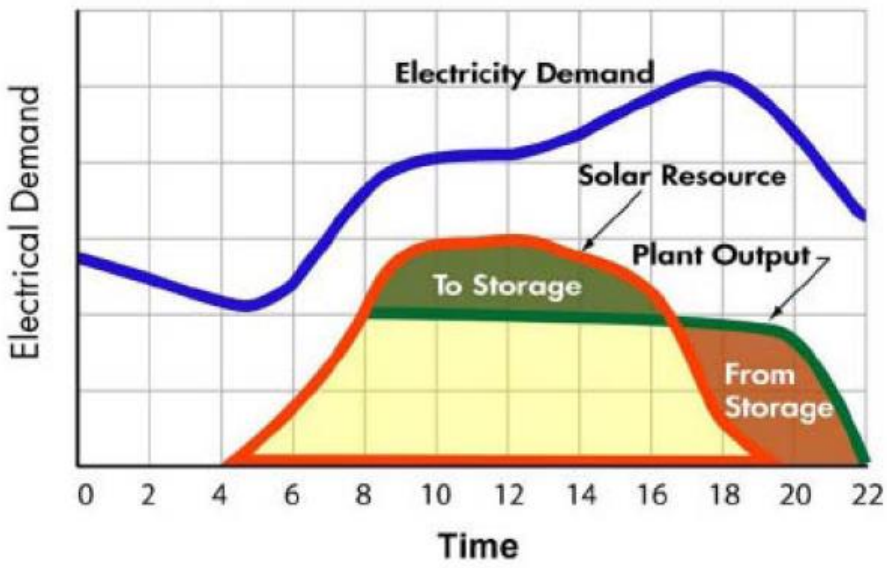
Storing "*low-cost electricity*"

- **Renewables**
  - PV
  - Wind



Having termal storage for STE means…

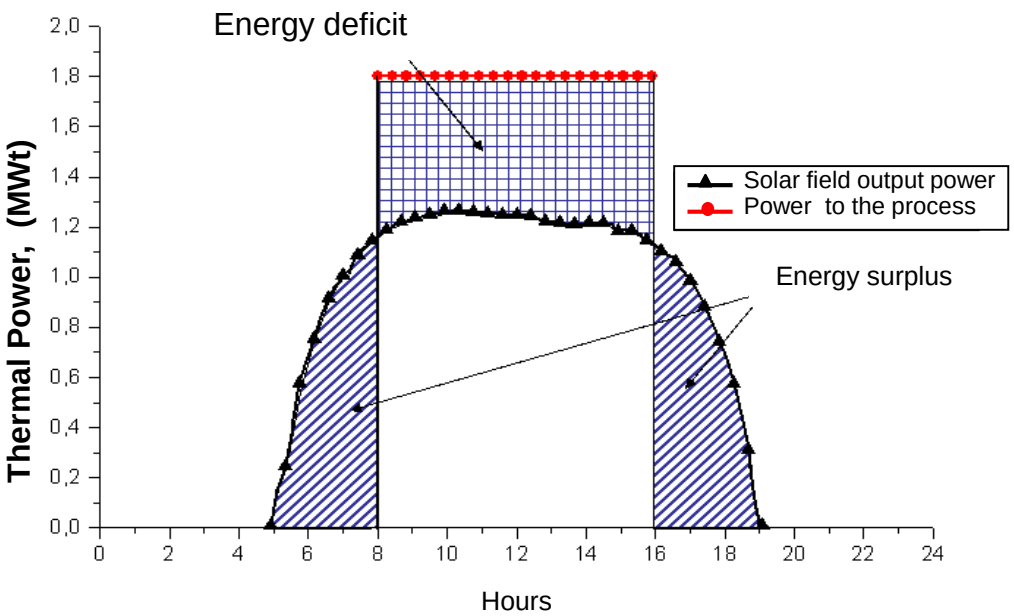
- Power generation becomes independent of solar resource
  - Overcome transients (clouds occurrence)
  - Extend operation time (during the night)



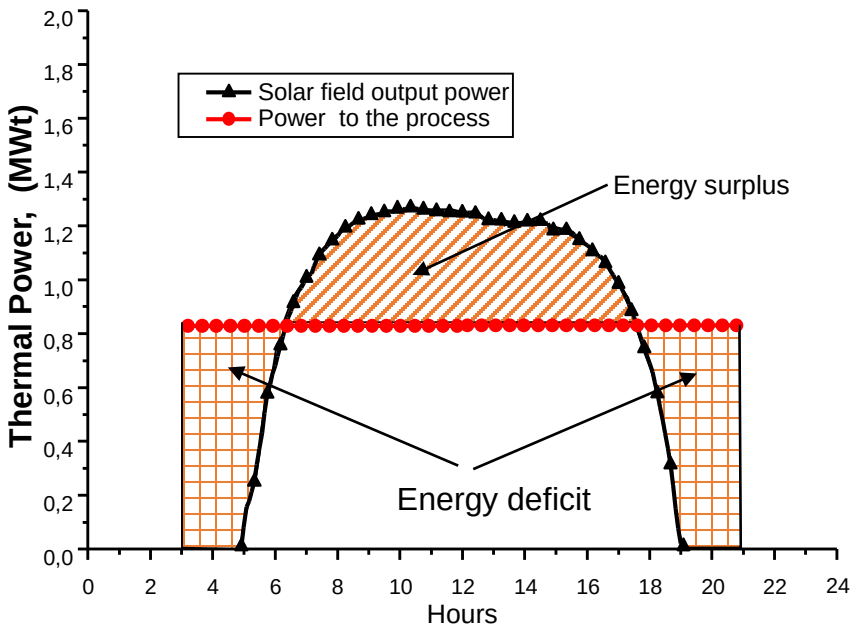
DISPATCHABLE ENERGY/POWER

Having termal storage for STE means…

- Power generation becomes independent of solar resource
  - Overcome transients (clouds occurrence)
  - Extend operation time (during the night)
  - Provide constant power



Case a)

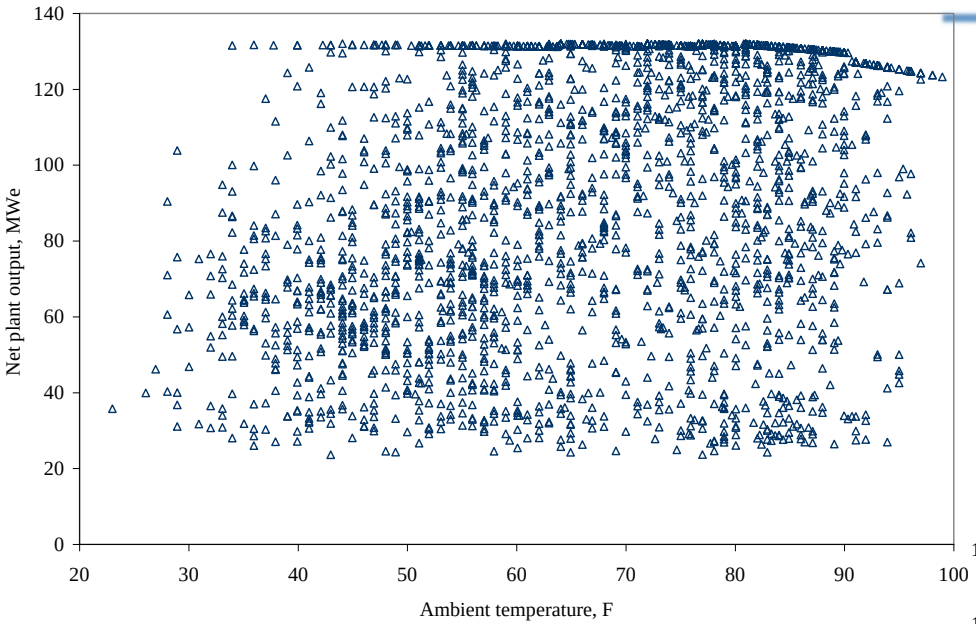


Case b)

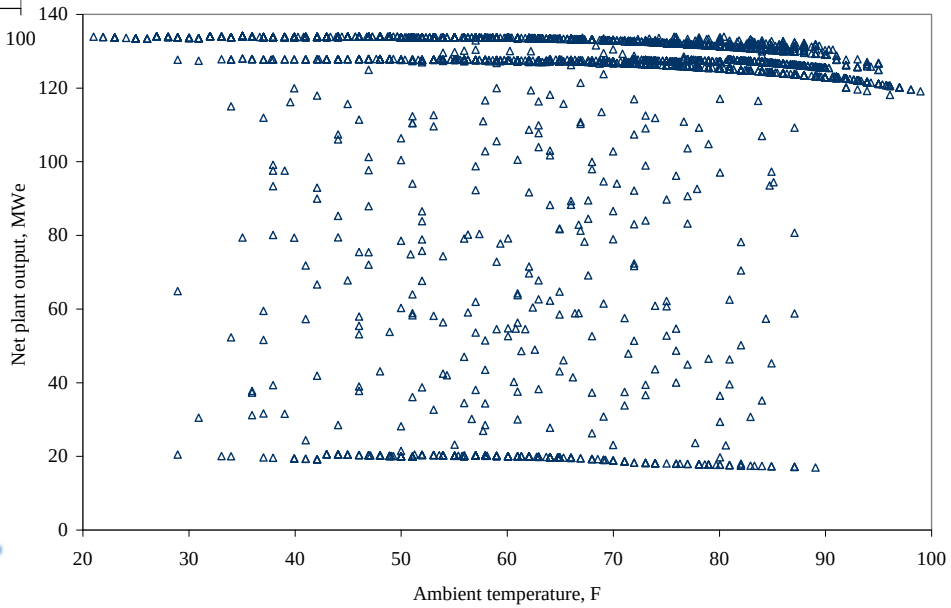
Having termal storage for STE means…

- Power generation becomes independent of solar resource
  - Overcome transients (clouds occurrence)
  - Extend operation time (during the night)
  - Provide constant power
  - Favors electrical production under nominal conditions
    - Increases the annual performance of he power block

Simulation of a 125 MWe STE plant without storage



And with 9 hours of storage



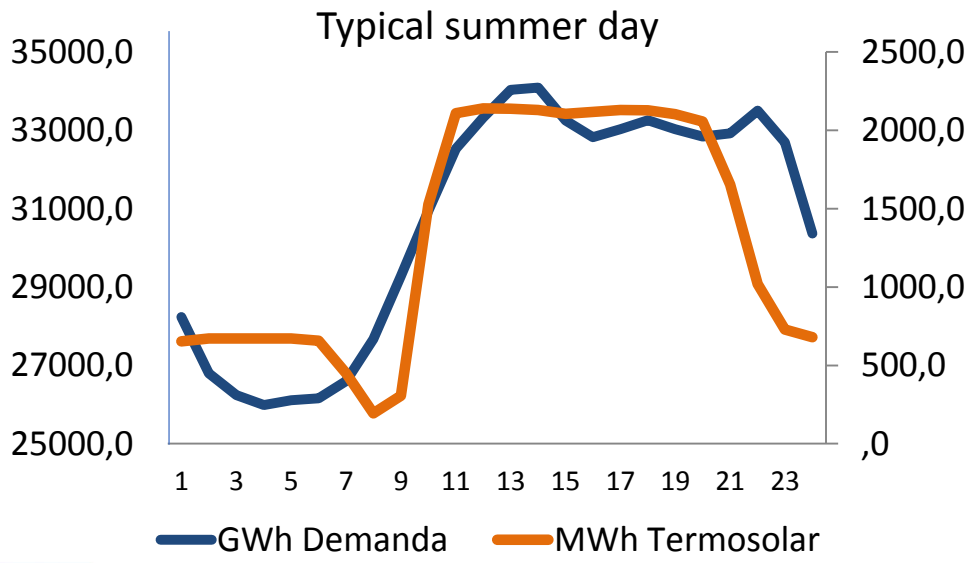
Having termal storage for STE means…

- Power generation becomes independent of solar resource
  - Overcome transients (clouds occurrence)
  - Extend operation time (during the night)
  - Provide constant power
  - Favors electrical production under nominal conditions
    - Increases the annual performance of he power block
  - Promoting other renewables to be integrated in the energy mix

‘Dispatchable’ implies that power production is well-forseen and managed

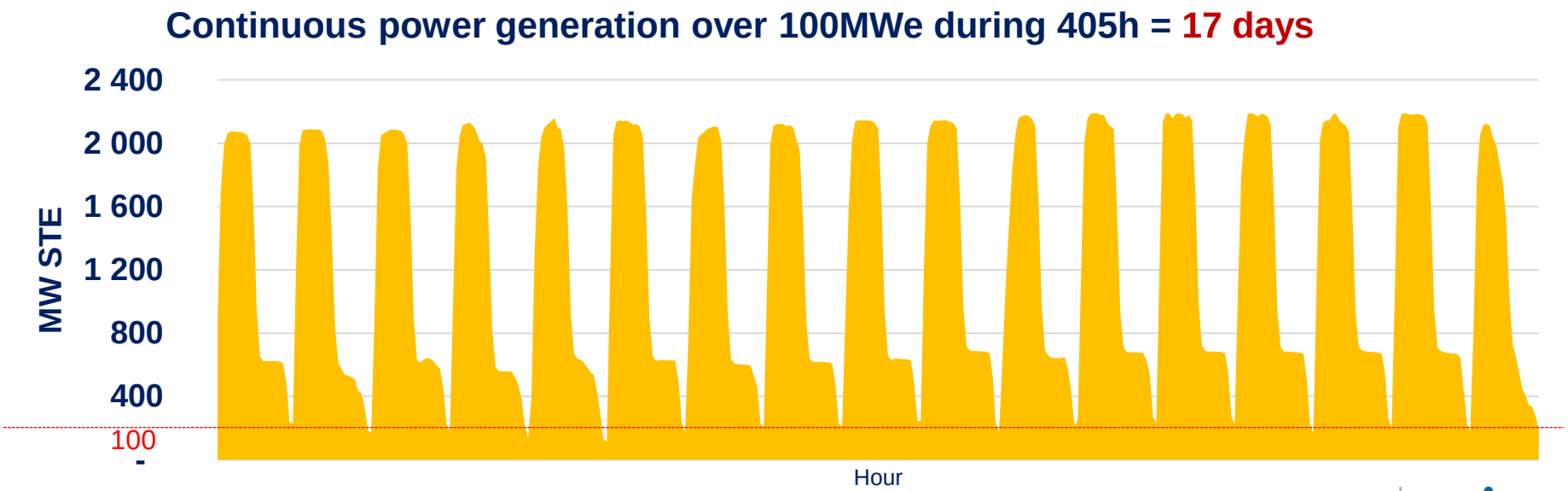
- Spanish case:
  - Around 2.3 GWe of STE installed
  - 40% STE plants have a 1GWh$_t$ TES

✓ Profiles of power provided by STE is similar to demand profile (see figure, left scale for GWh demand and right scale for STE power generation)



Example of continuous STE power generation in Spain

With large thermal energy storage systems STE plants can provide base load



July 2018 data

STE's treasure

Commercial Thermal Storage Systems with large capacity mean:

- For the owner: electricity sold when the pool price is higher (more profit)
- For System operator : **Dispatchability**, Grid stability

Higher total system COST

Higher cost for backup conventional systems

"variable" generation technologies

More NON-dispatchable systems

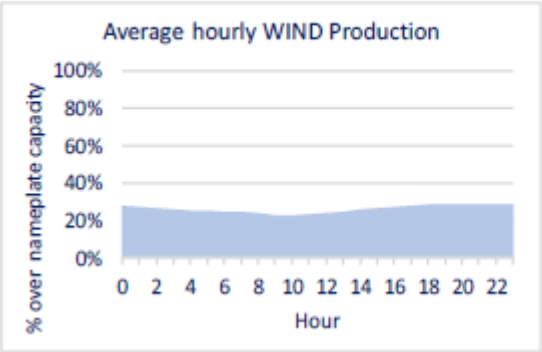
More back-up conventional systems

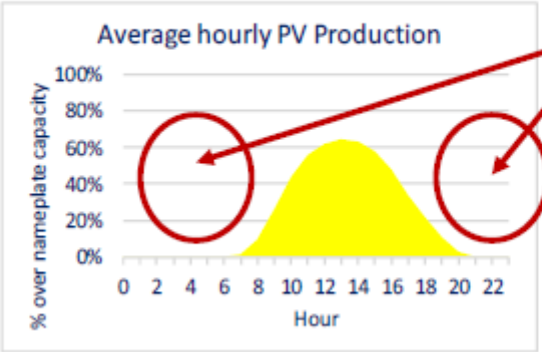
Storage implies a c$ 3-4 / kWh differential value compared with non-dispatchable generation systems

STE is the necessary piece for a renewable-base generation mix

Complementarity of STE with PV and Wind

Typical yearly generation profiles of the most deployed renewable technologies

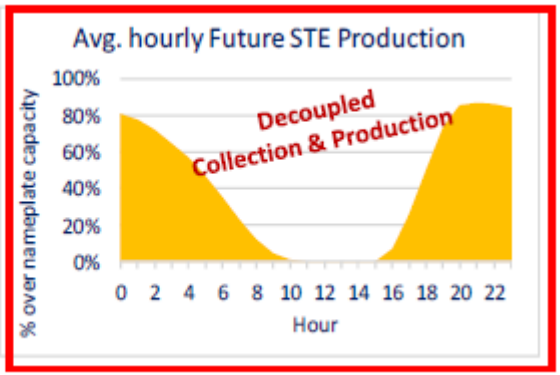




Average hourly production on a long historical series

Which technology could fill up these gaps?

What is the missing piece?



PROTERMOSOLAR Electrical Sector Transition Report

Study based on real hourly data of demand and power generation with different RES

www.protermosolar.com

(English presentation at https://www.protermosolar.com/wp-content/uploads/2019/02/Protermosolar-Transition-Report.012019.pdf)

Generation data of all technologies in previous years → Proposed mix in 2030 * → Demand forecast by 2030

- How much backup is required?
- What is the generation cost?
- What is the emission level?

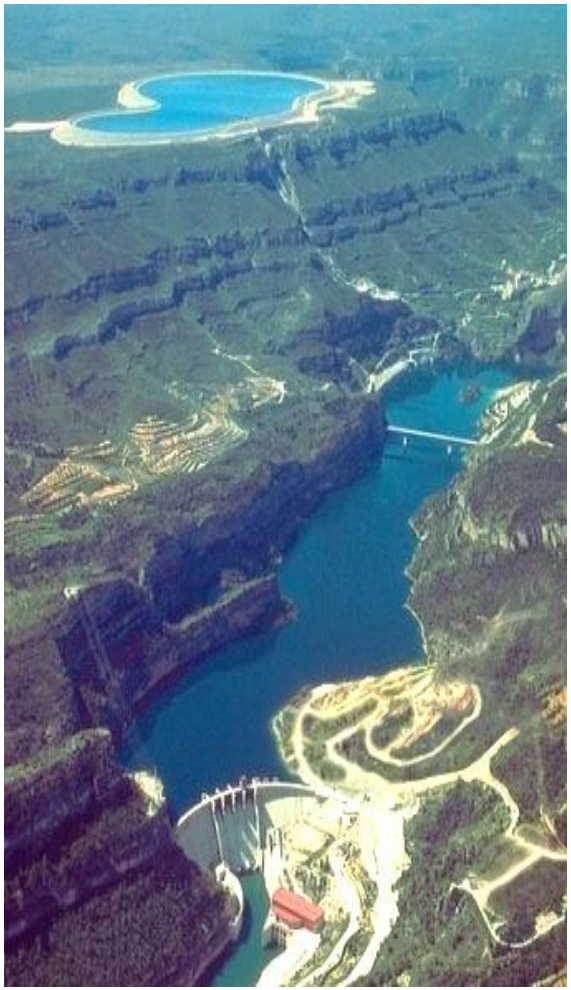
Impacts of having TES of large capacity

1. Impacts on the Power network
   - ✓ Promoting an energy mix with RES, not only STE but also others like wind and PV
   - ✓ Possibility to use dumping electricity from wind and PV
   - ✓ Permanent back-up capacity at low cost

Benefits of using large TES systems for back-up

50 STE plants, each of 100MWe and with 12hour TES, could provide a strategic back-up of 30GWh$_e$ without additional investment.

The cost of pumping power stations for the same capacity would be of 7.500 Mio €



Impacts of having TES of large capacity

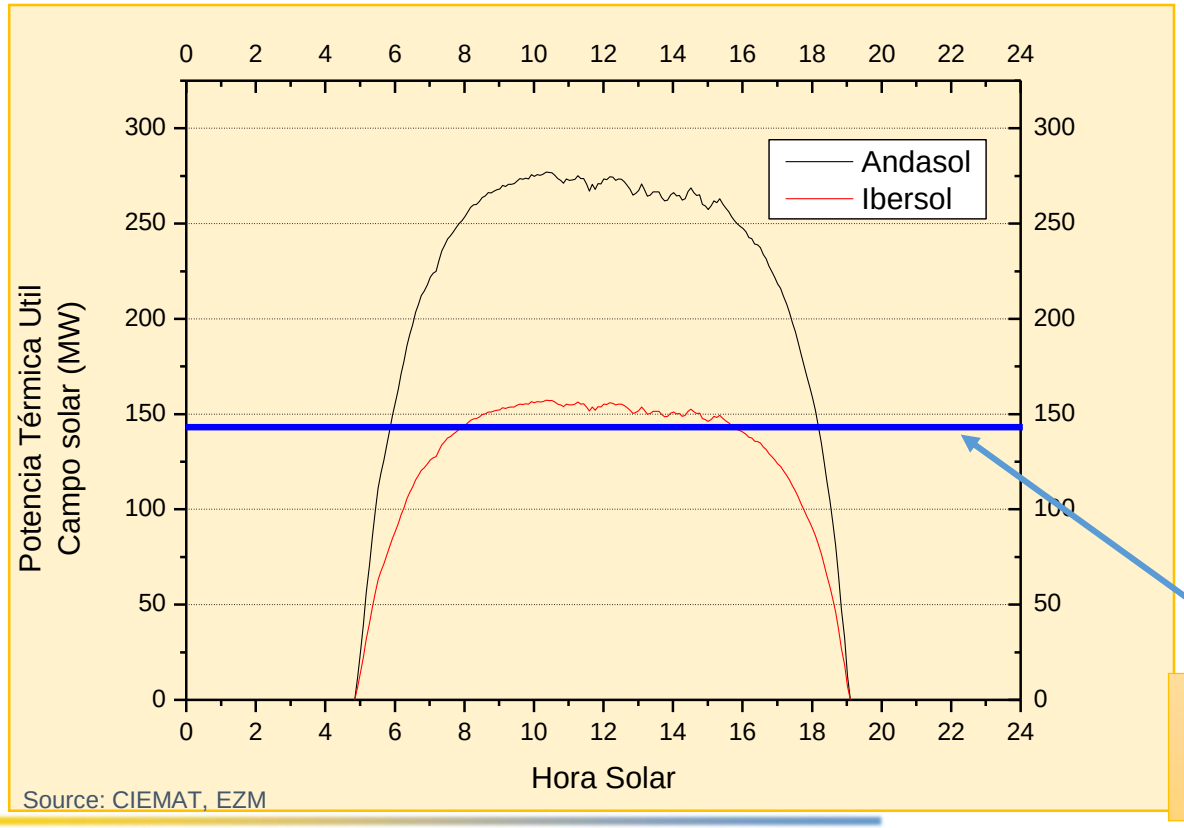
- Impacts on the Power network
  - ✓ Promoting an energy mix with RES, not only STE but also others like wind and PV
  - ✓ Possibility to use dumping electricity from wind and PV
  - ✓ High back-up capacity at low cost

- Impacts on Plant management
  - ✓ Dispatchable power production to meet the peak demand

- Impact on the STE plant
  - ✓ Adding a new subsystem
  - ✓ Bigger solar field

Impacts of having TES of large capacity

The size of the solar field depends not only on the nominal electric power of the plant but also on the existence or not of a thermal energy storage (TES) system and on its capacity.



Source: CIEMAT, EZM

<u>With thermal storage (Andasol)</u>

- 50 MWe nominal power
- 510000 m^2 of PTCs

Thermal storage 1000 MWh

<u>Without thermal storage (Ibersol)</u>

- 50 MWe nominal power
- 288000 m^2 of PTCs

NO thermal energy storage

Thermal power required by the power block (50 MWe)

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Commercial TES Systems: Two-tank systems

- **Most widely used in commercial STE plants**
- Solar salt as storage media

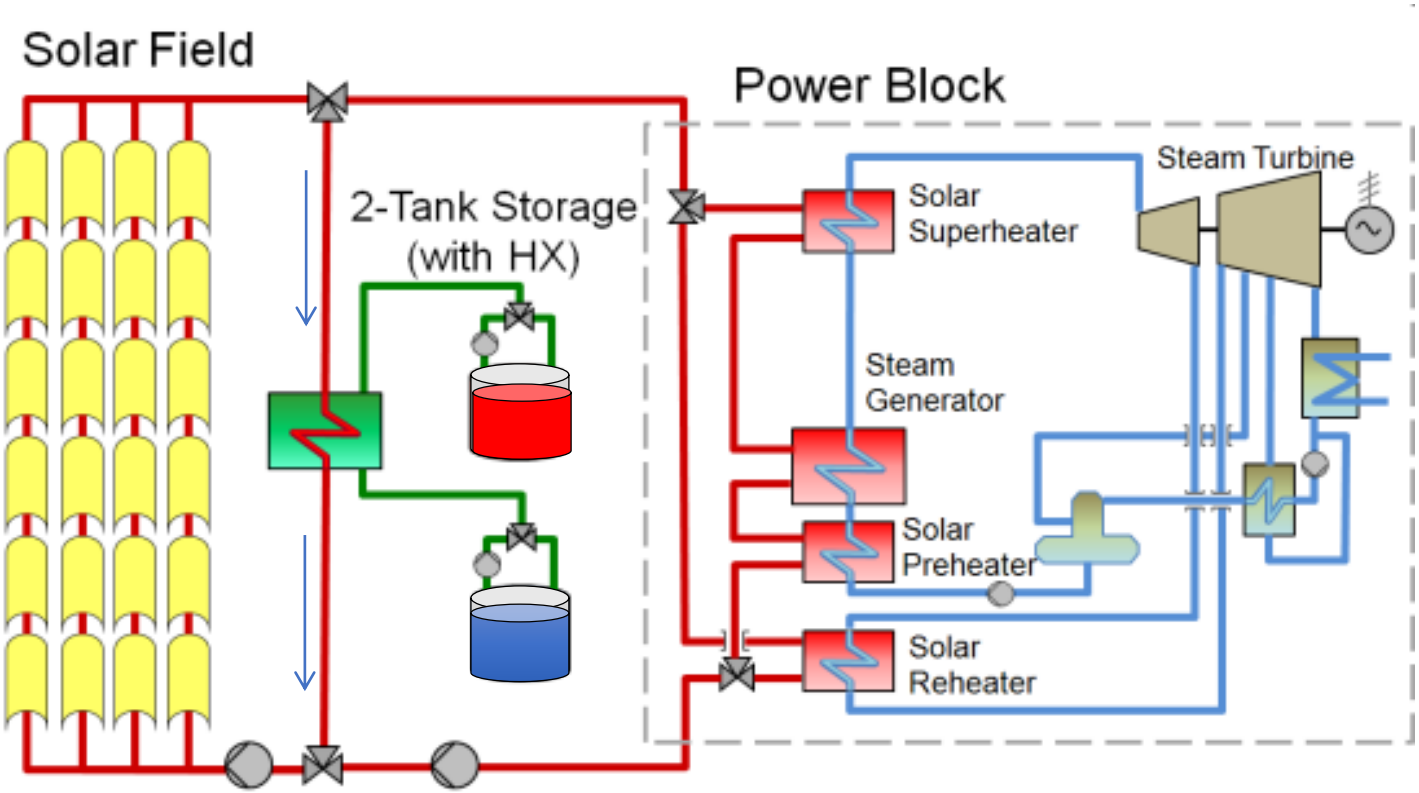
SOLAR SALT: Non-eutectic mixture of nitrate salts:

w-60%NaNO3+w-40%KNO3

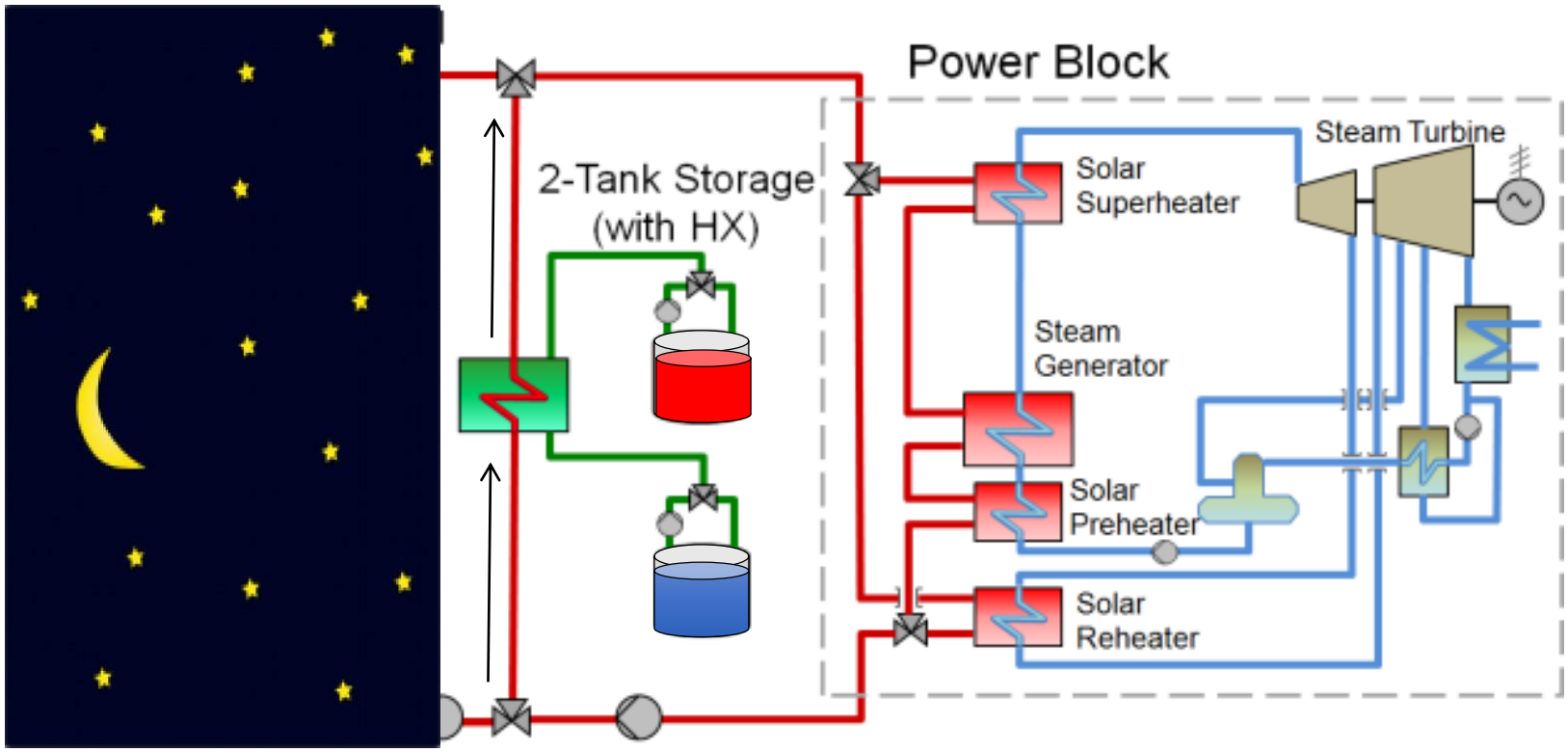
Why Solar Salt?

- ☺ Maximum working temperature ~575ºC
- ☺ High thermal capacity (~2800 kJ/m^3 ºC)
- ☺ Low vapour pressure
- ☺ Non explosive or hazardous material
- ☺ Previous experiences in Solar Two (USA, 105 MWh), CESA-1 (Spain, 12MWh), Themis (France, 40MWh), CRTF (NM,USA, 7MWh)
- ☹ At 240 ºC they solidify
- ☹ Corrosion issues specially at high temperatures

Two tank storage system. Charging



Two tank storage system. Discharging



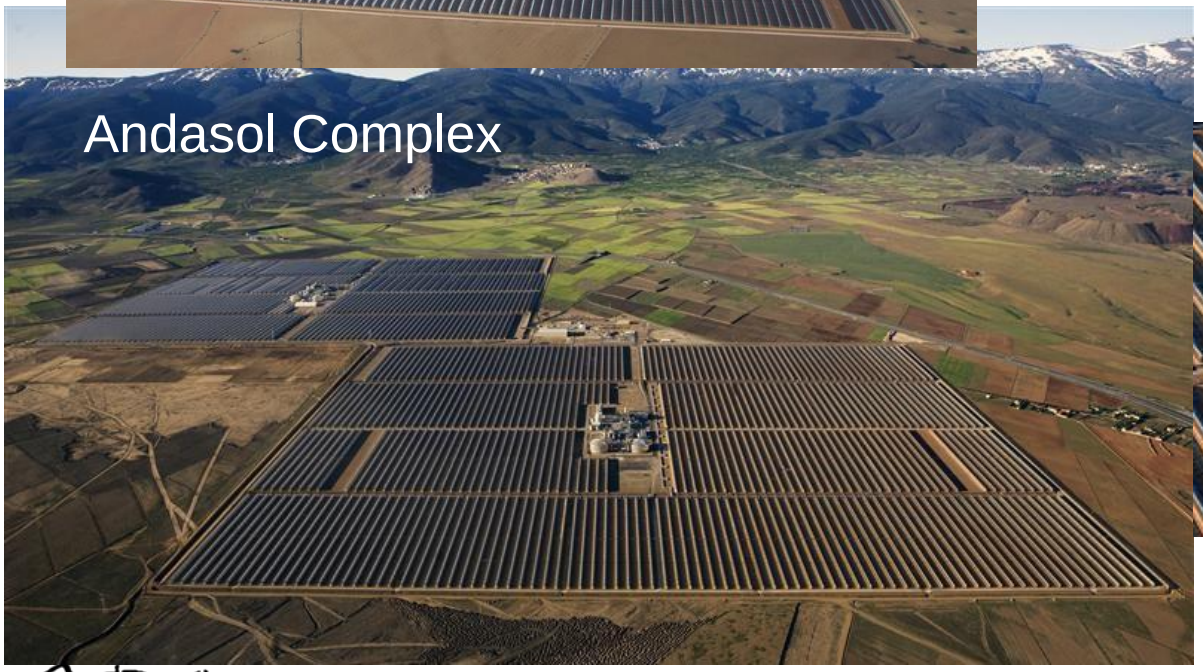
Examples of commercial parabolic trough plants with TES

Spanish case :

- 50 MWe
- Oil as HTF => 293ºC (cold tank) & 393ºC (hot tank)
- 7.5 h of storage in two-tank solar salt storage system:

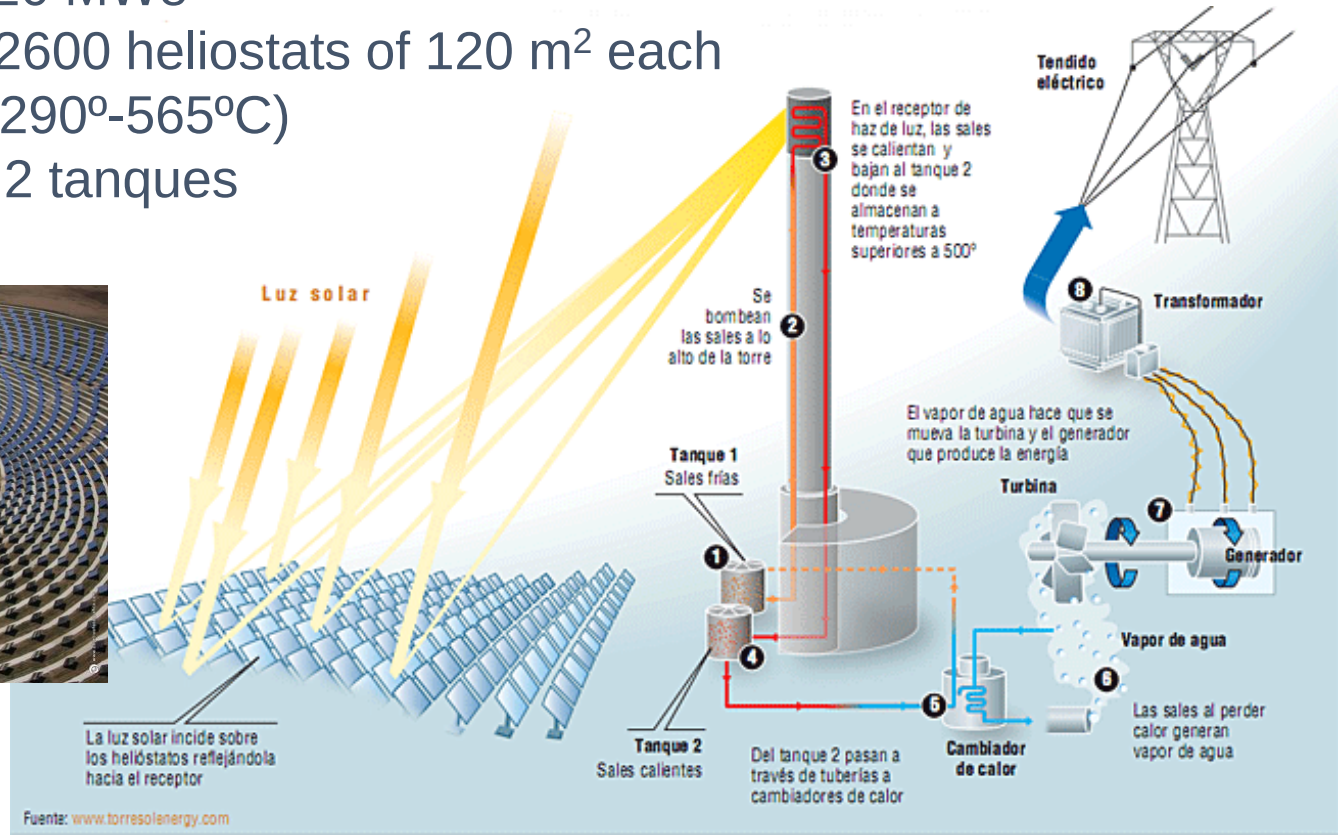
  2 tanks of Ø~ 36 m x H~14 m

  ~28000 Tons of salts



GemaSolar: 1st commercial tower plant with storage

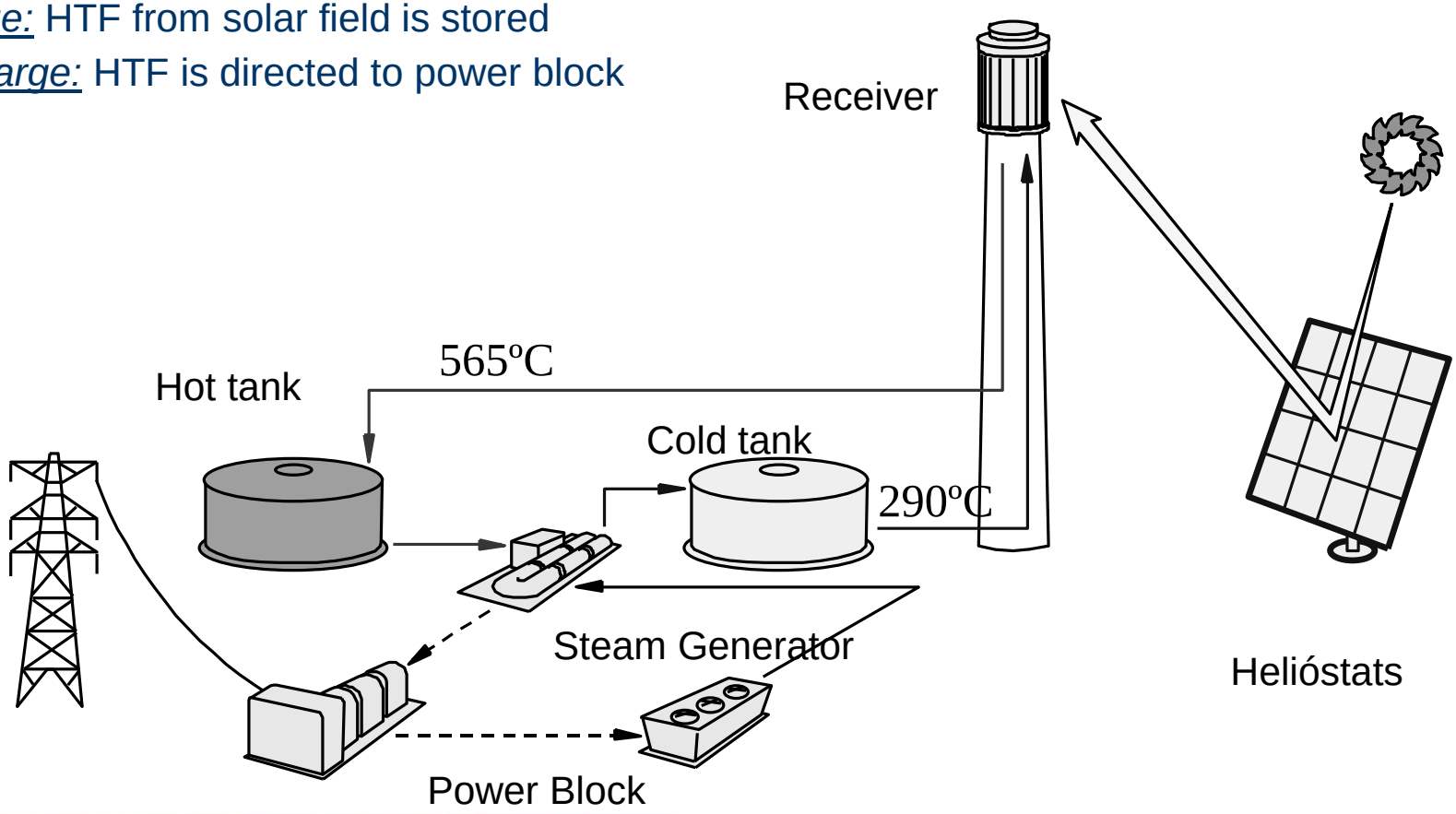
- Located ay Fuentes de Andalucía (Sevilla)
- Owned by Torresol Energy
- Nominal power:20 MWe
- 140m tower & : 2600 heliostats of 120 m^2 each
- HTF: solar salt (290º-565ºC)
- 15 h of storage, 2 tanques



http://www.torresolenergy.com/TORRESOL/inicio/es

Sensible heat storage: principles

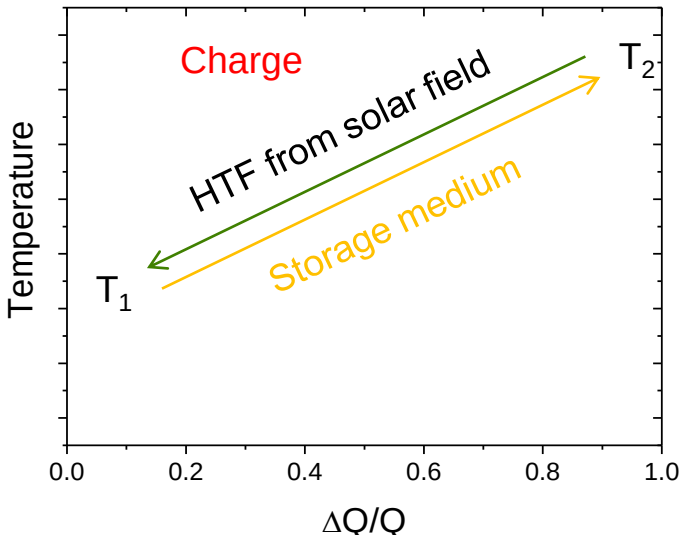
- There is a temperature change in the storage medium
- **Direct storage**:
  - *Charge:* HTF from solar field is stored
  - *Discharge:* HTF is directed to power block



Sensible heat storage: principles

- There is a temperature change in the storage medium
- **Direct storage**:
  - *Charge:* HTF from solar field is stored
  - *Discharge:* HTF is directed to power block
- **Indirect storage:**
  - *Charge:* HTF from solar field transfers energy to storage medium

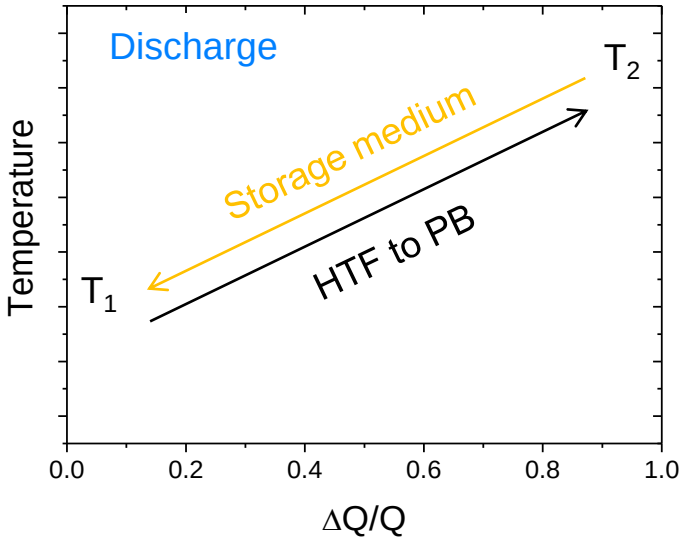
Indirect storage (HTF≠storage medium)



Sensible heat storage: principles

- There is a temperature change in the storage medium
- **Direct storage**:
  - *Charge:* HTF from solar field is stored
  - *Discharge:* HTF is directed to power block
- **Indirect storage:**
  - *Charge:* HTF from solar field transfers energy to storage medium
  - *Discharge:* Storage medium transfers energy to HTF going to power block

Indirect storage (HTF≠storage medium)

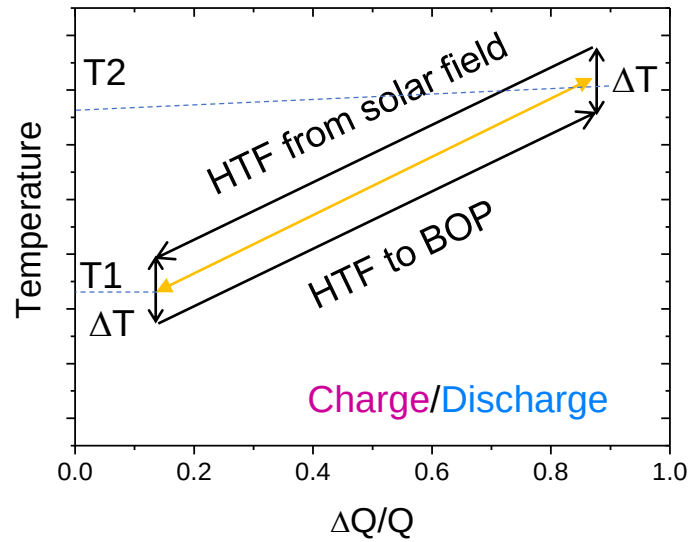


Sensible heat storage: principles

- There is a temperature change in the storage medium
- **Direct storage**:
  - *Charge:* HTF from solar field is stored
  - *Discharge:* HTF is directed to power block
- **Storage capacity** (kWh) depends on temperature interval in the storage medium: $\Delta Q = m \cdot C_p \cdot (T_2 - T_1)$ ⇨(>0 in charge; <0 in discharge) ⇨T_2-T_1
- For **liquid storage media**:
  - Heat transfer mechanism is convection
  - Discharge power may be kept constant
- For **solid storage media**:
  - Heat transfer mechanism is conduction
  - Discharge power might not be constant

- **Indirect storage:**
  - *Charge:* HTF from solar field transfers energy to storage medium
  - *Discharge:* Storage medium transfers energy to HTF going to power block
  - There is a temperature gap in HTF between charge and discharge (ΔT)

Indirect storage (HTF≠storage medium)



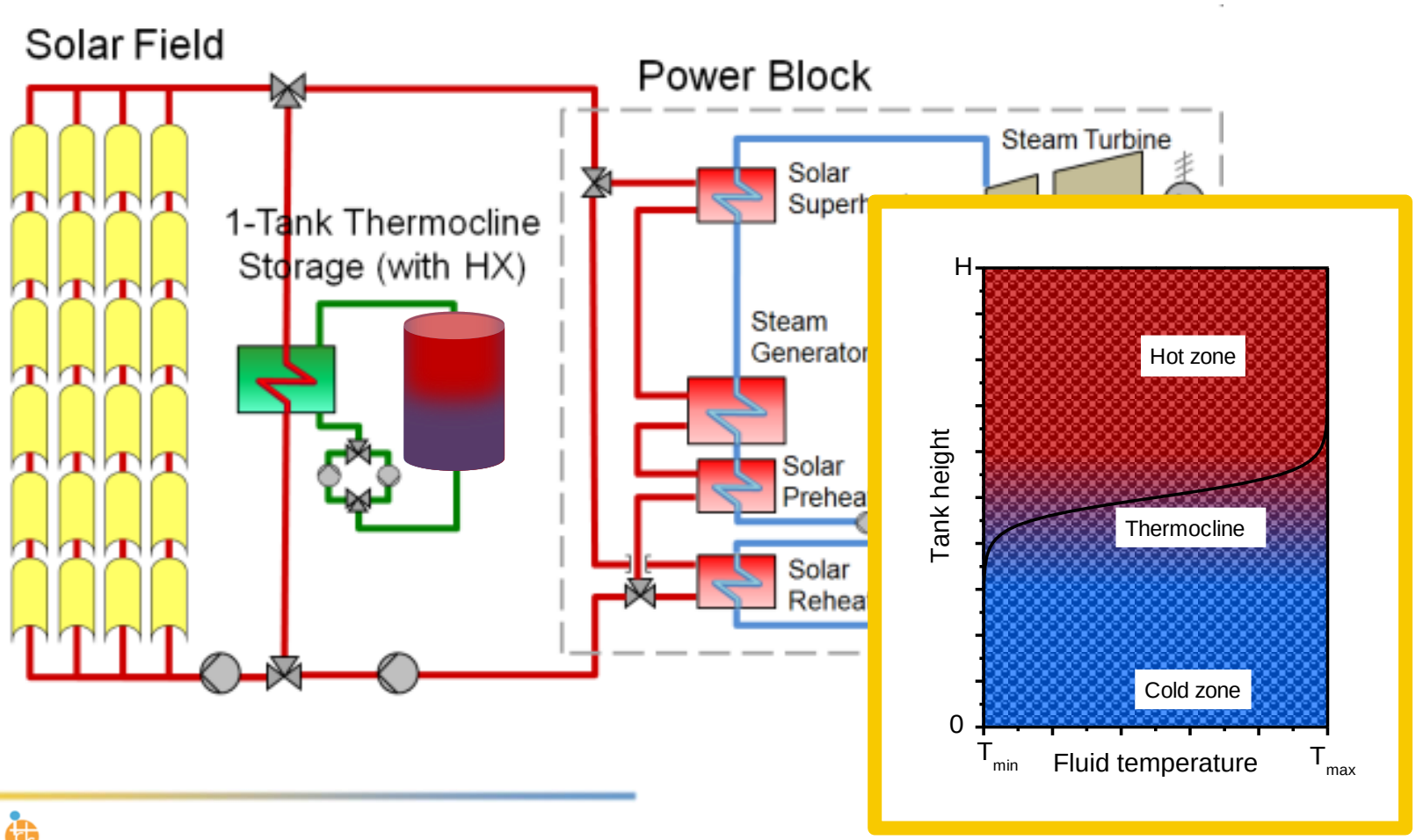
Sensible heat storage: storage medium requirements

- **High volumetric thermal capacity, ρC_p**
  - Solar salt (60%NaNO3+40%KNO3): ~2800 kJ/m^3 ºC
  - Sinthetic oil: ~ 1900 kJ/m^3 ºC
  - water: ~ 4200 kJ/m^3 ºC
  - concrete: ~2500 kJ/m^3 ºC
  - rocks: ~2700 kJ/m^{3}K
  - Vitrified industrial wastes (Cofalit y Plasmalit): ~3000 kJ/m^{3}K
- **Low vapor pressure for liquid media** → avoiding presurized tanks
  - Water has to be under pressure: 30bar/230ºC; 100bar/311ºC (*)
  - Therminol VP1 has a vapor pressure of 11bar at 395ºC
- **Stable** in the temperature range of operation, **(T_1, T_2)**
- **Non explosive or hazardous materials**
- **Low price materials**

Molten salts fulfil these requirements

Configurations of sensible heat storage:

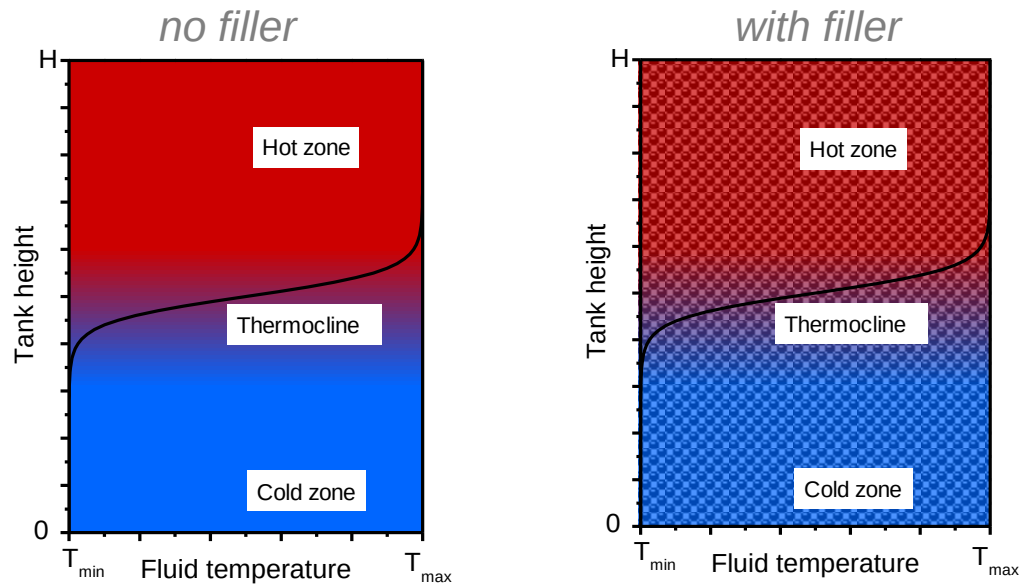
Single tank system. Thermocline



Thermocline tank: benefits and drawbacks

ADVANTAGES:

- Just one tank ⇨ expected cost reduction up to 33%
- Having a solid filler ⇨cost reduced down to 75%



CHALLENGES

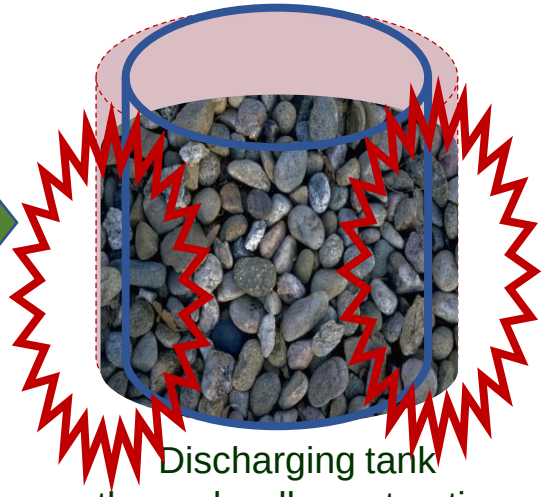
- Thermocline region degradation
- Having a solid filler ⇨ Compatibility of media (HTF and filler)
- Having a solid filler ⇨ Thermal ratcheting

Thermal ratcheting

potential unfordable
mechanical stresses!!!:
for the walls and/or the filler

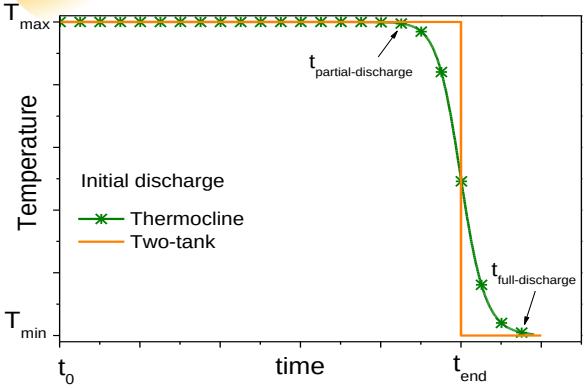
Discharged tank
cold wall tank and filler

Charging tank
thermal walls expansion



Discharging tank
thermal walls contraction

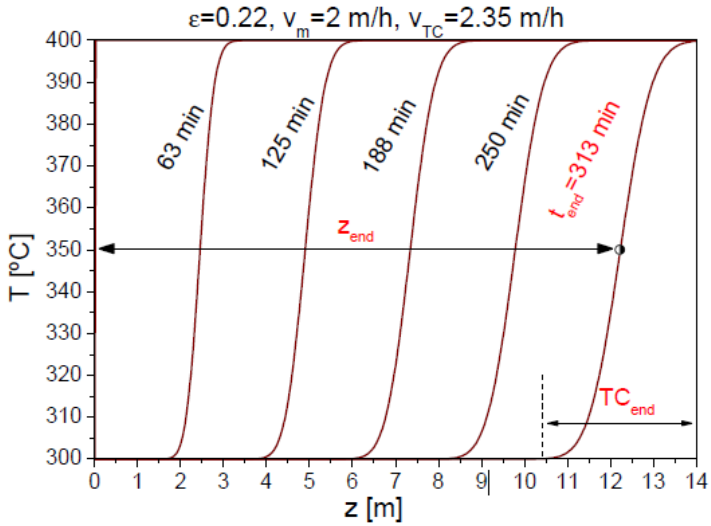
Thermocline region behavior



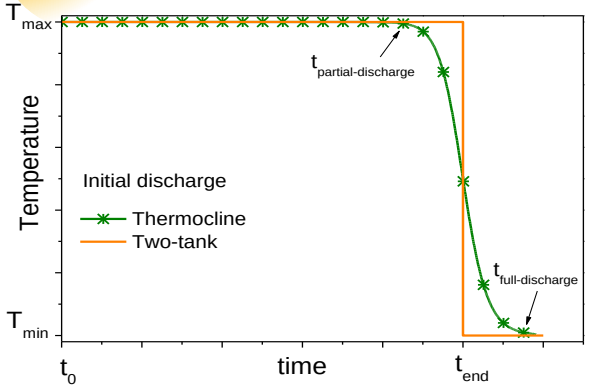
- **Not all the energy is useful for power generation:**

  For a similar capacity thermocline tank need a bigger tank size than each tank in a two-tank configuration

- **Thermocline region increases its size along the time**



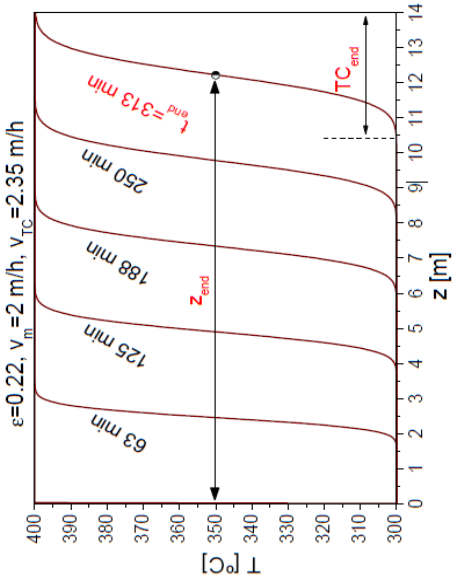
Thermocline region behavior



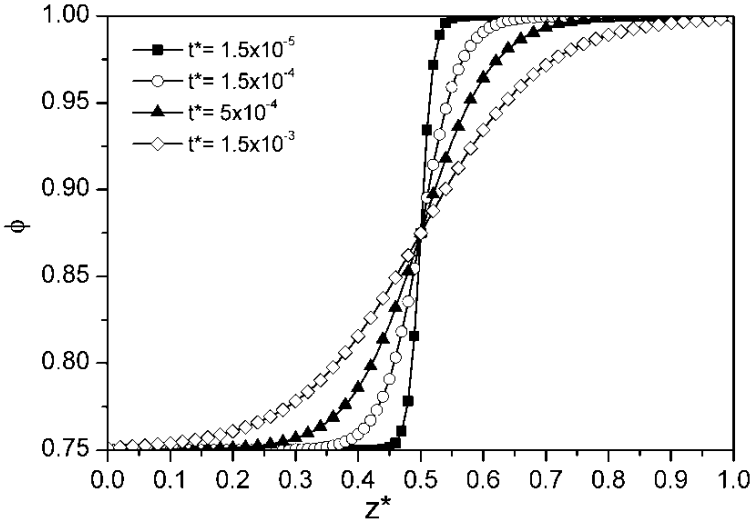
Not all the energy is useful for power generation:

For a similar capacity thermocline tank need a bigger tank size than each tank in a two-tank configuration

➢ **Thermocline region increases its size along the time**



during charging/discharging processes



and during stand-by situations

Thermocline tank requires…

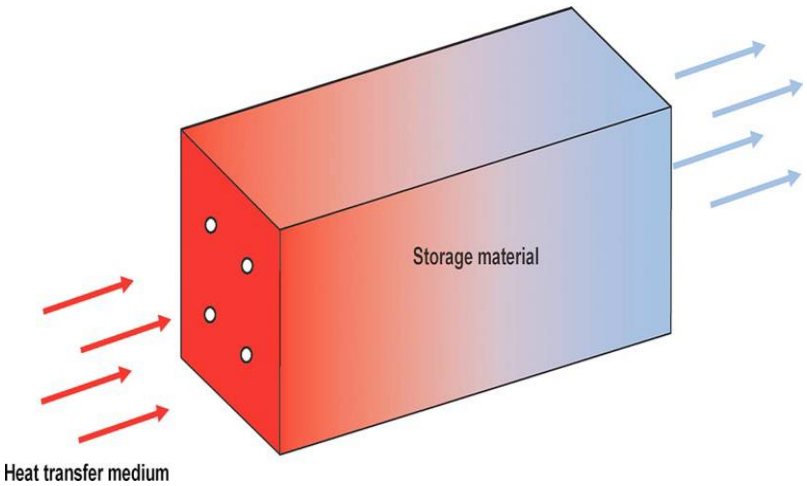
Extracting (remove) completely the thermocline region out of the tank

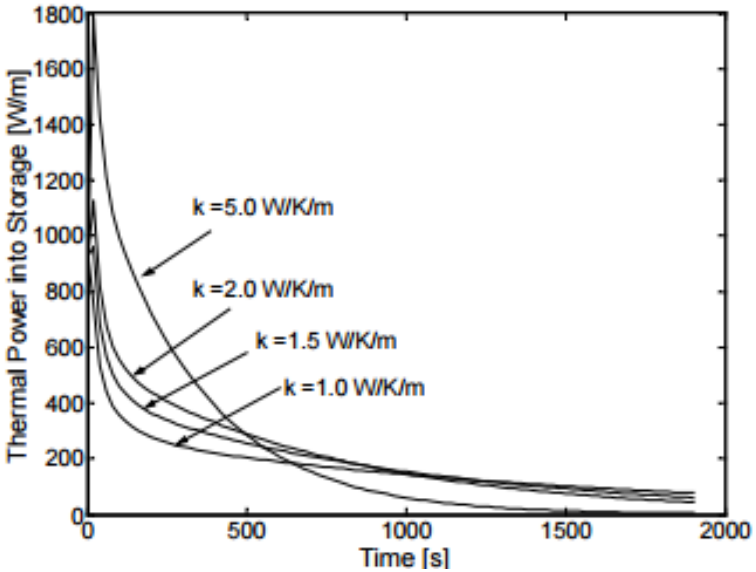
What to do with this energy?

- Solar field preheating during start-up
- Steam turbine preheating before starting operation
- ……..

Sensible heat in solids (I)

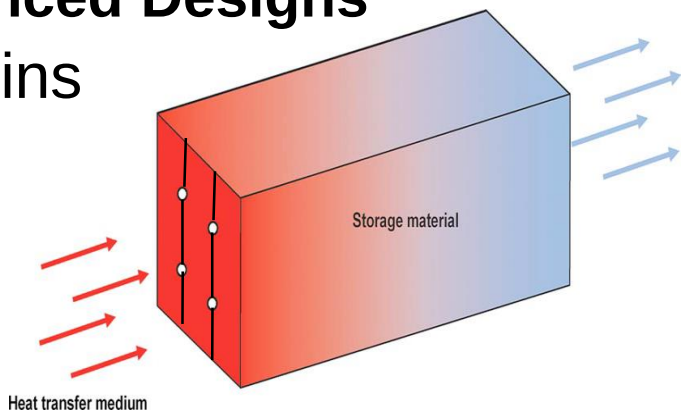
- **Special Concrete** (~2500 kJ/m^{3}K), ceramic, industrial wastes (Cofalit, Plasmalit)
- Mechanical strength is critical
- **Conduction** is the main heat transfer mechanism ($k_{típica}$≤1.5 W/mK)

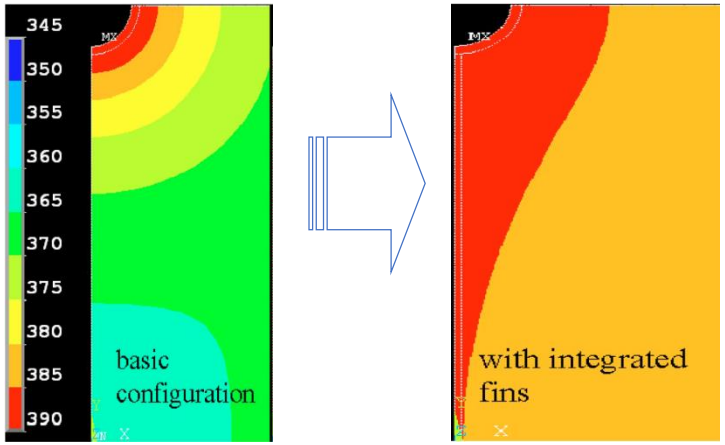




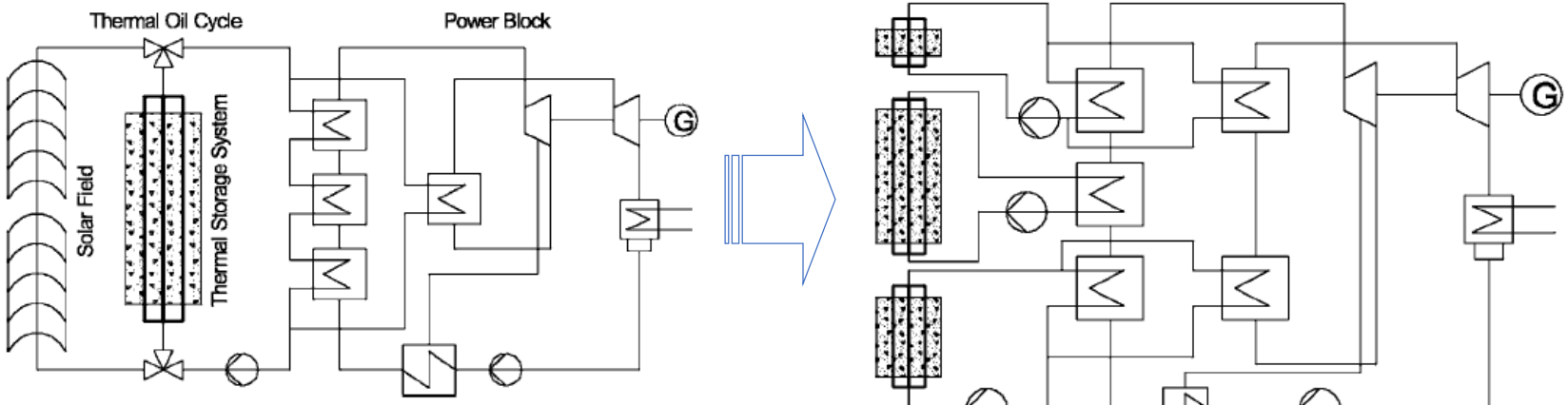
Sensible heat in solids (II)

- **Enhanced Designs**
  - ➢ Fins





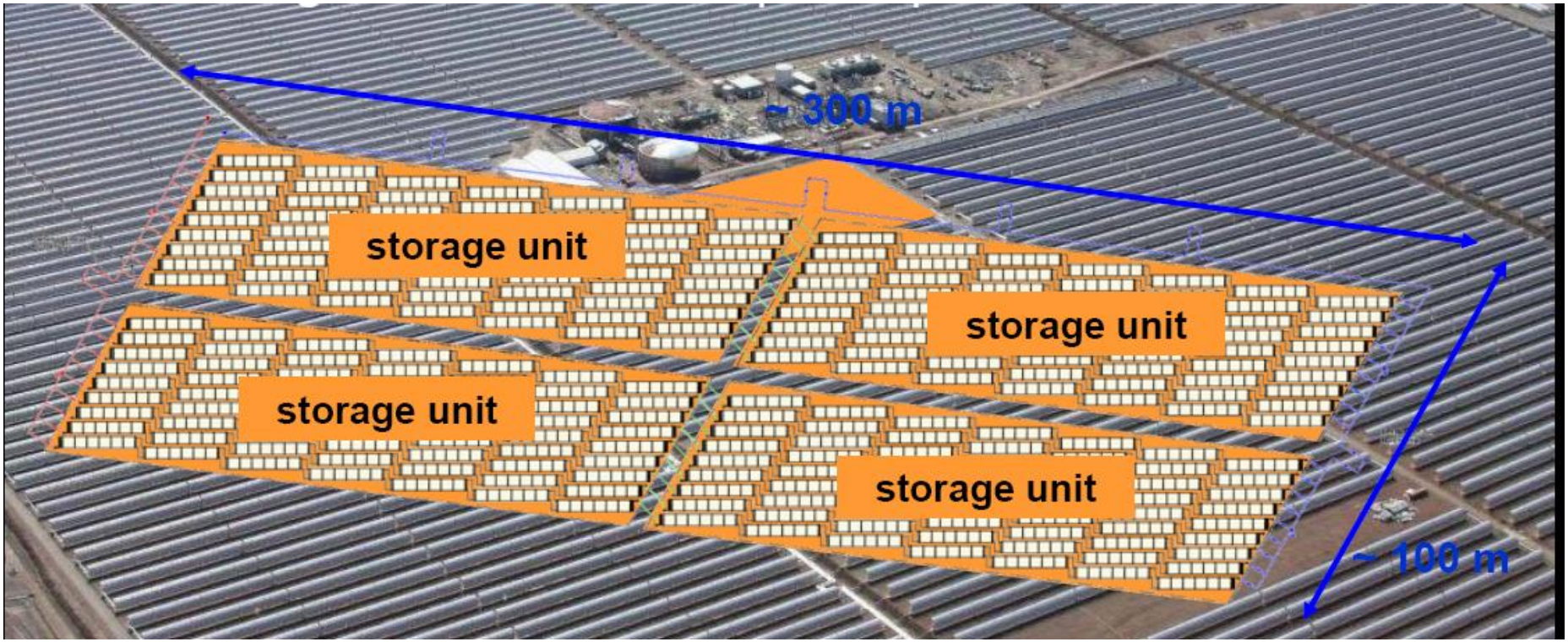
- **Modular systems** (smaller ΔT: ΔT= ΔT1+ ΔT2+ ΔT3)



D. Laing et al., 2008, J. Solar Energy Engineering, *V 130.*

Size comparison of concrete and 2-tanks with molten salts for 1GWht of capacity

The plot of land required is 5 times smaller for molten salt system



Laing, 2008

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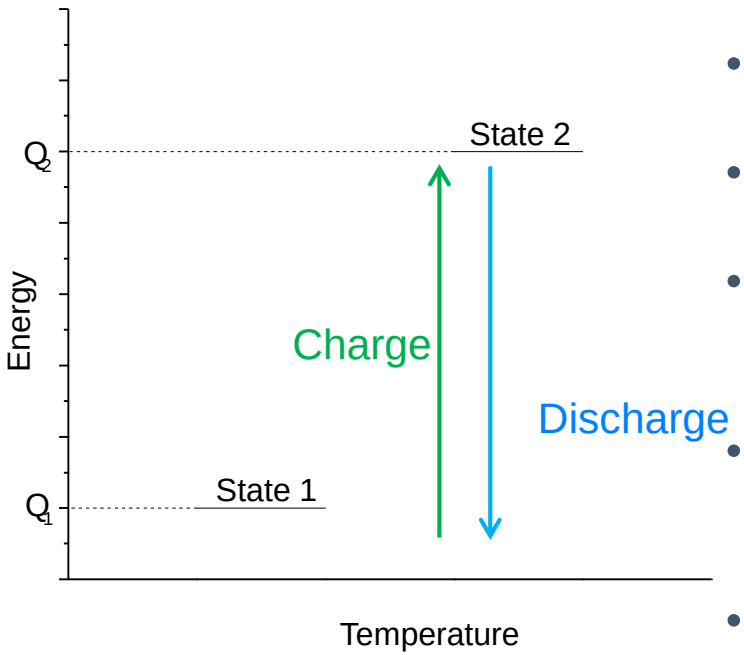
Latent heat storage. Fundamentals

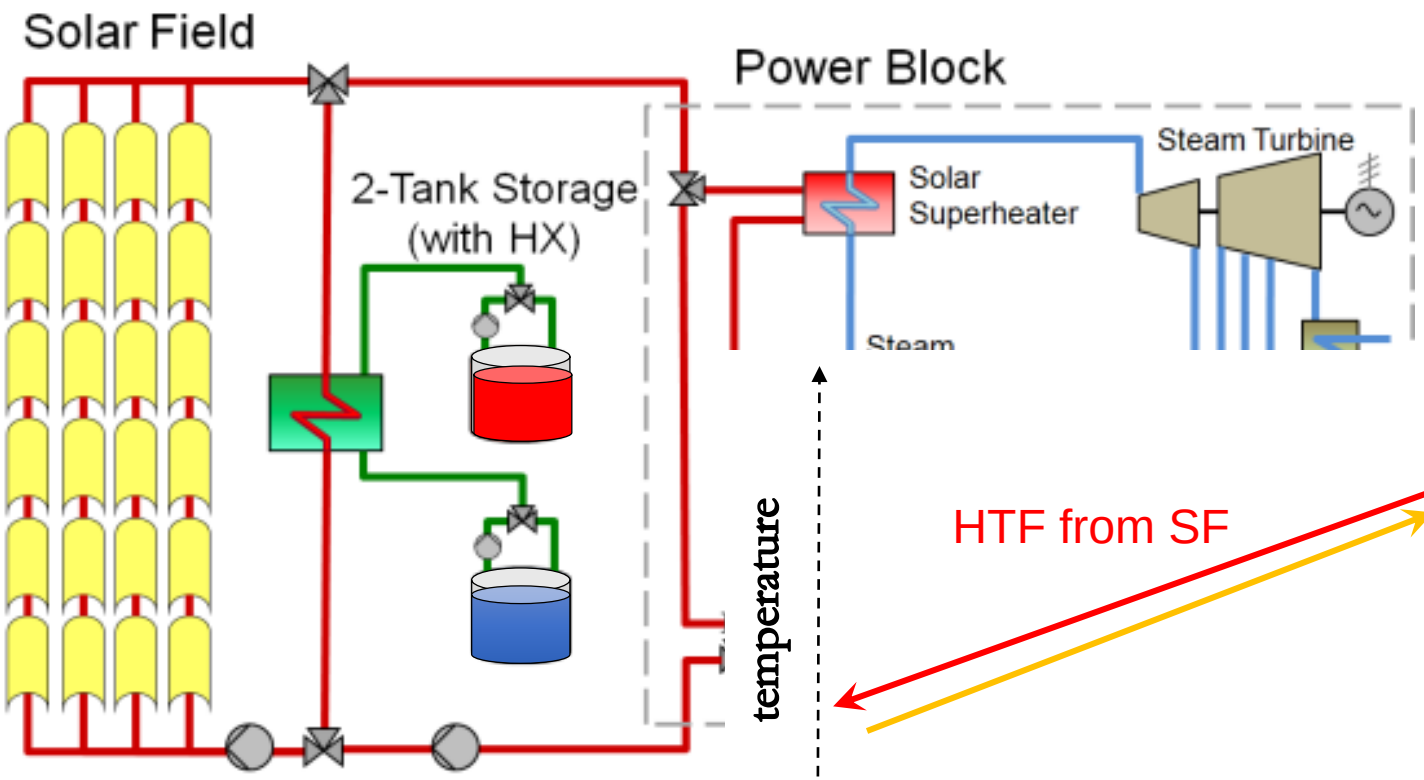
- The storage medium **undergoes a phase change** ⇨Phase change material (PCM)

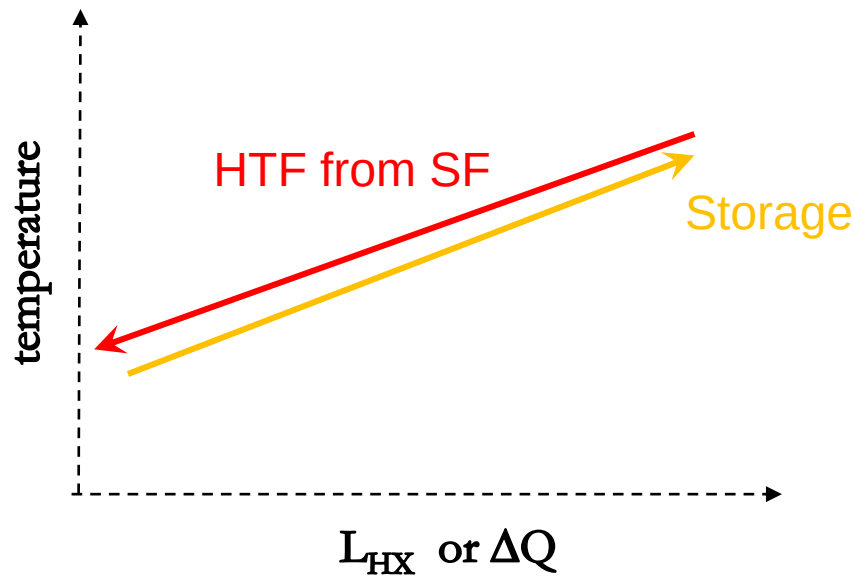


- <u>Charge process</u>: $Q_{TES}=Q_2-Q_1=m_{PCM}\cdot\Delta H_{phase}>0$
- <u>Discharge proccess</u>: $Q_{TES}=Q_1-Q_2= m_{PCM}\cdot\Delta H_{phase}<0$
- Storage capacity, Q_{TES}, depends on Latent enthalpy, ΔH_{phase}
- PCM is chosen taking into consideration its phase change temperature, T_{phase}
- T_{phase} is imposed by the system delivering the energy to be stored

Is an Andasol type STE plant appropriate for a latent storage system?

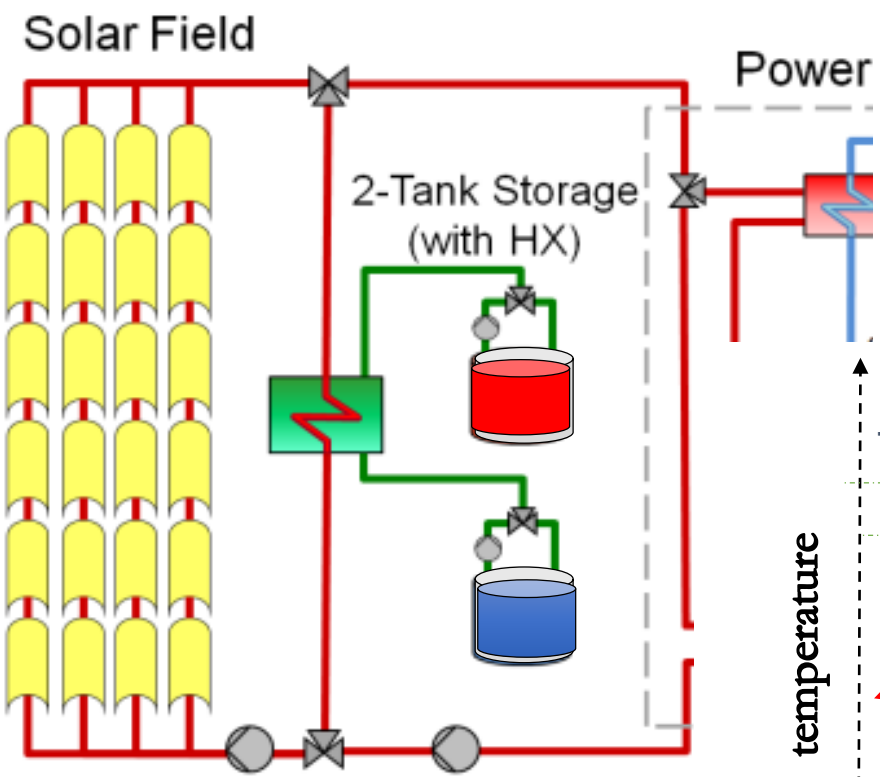
Charge

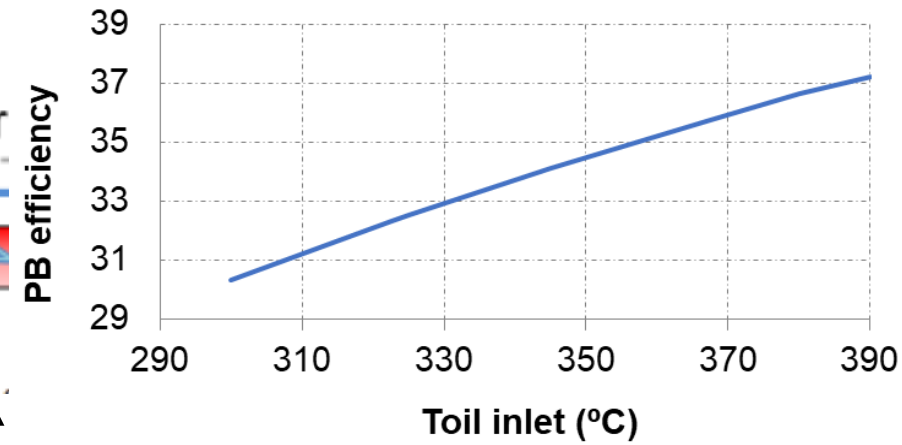


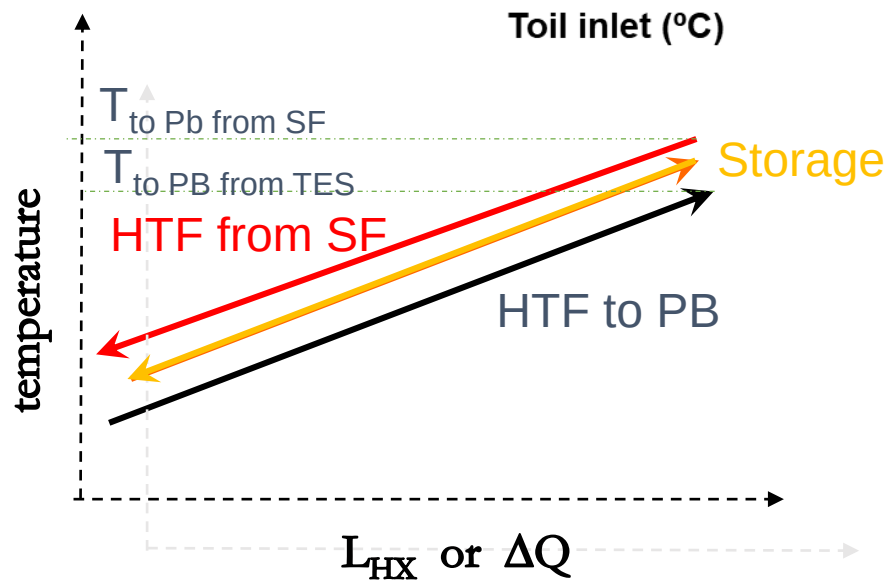


Is an Andasol type STE plant appropriate for a latent storage system? (II)

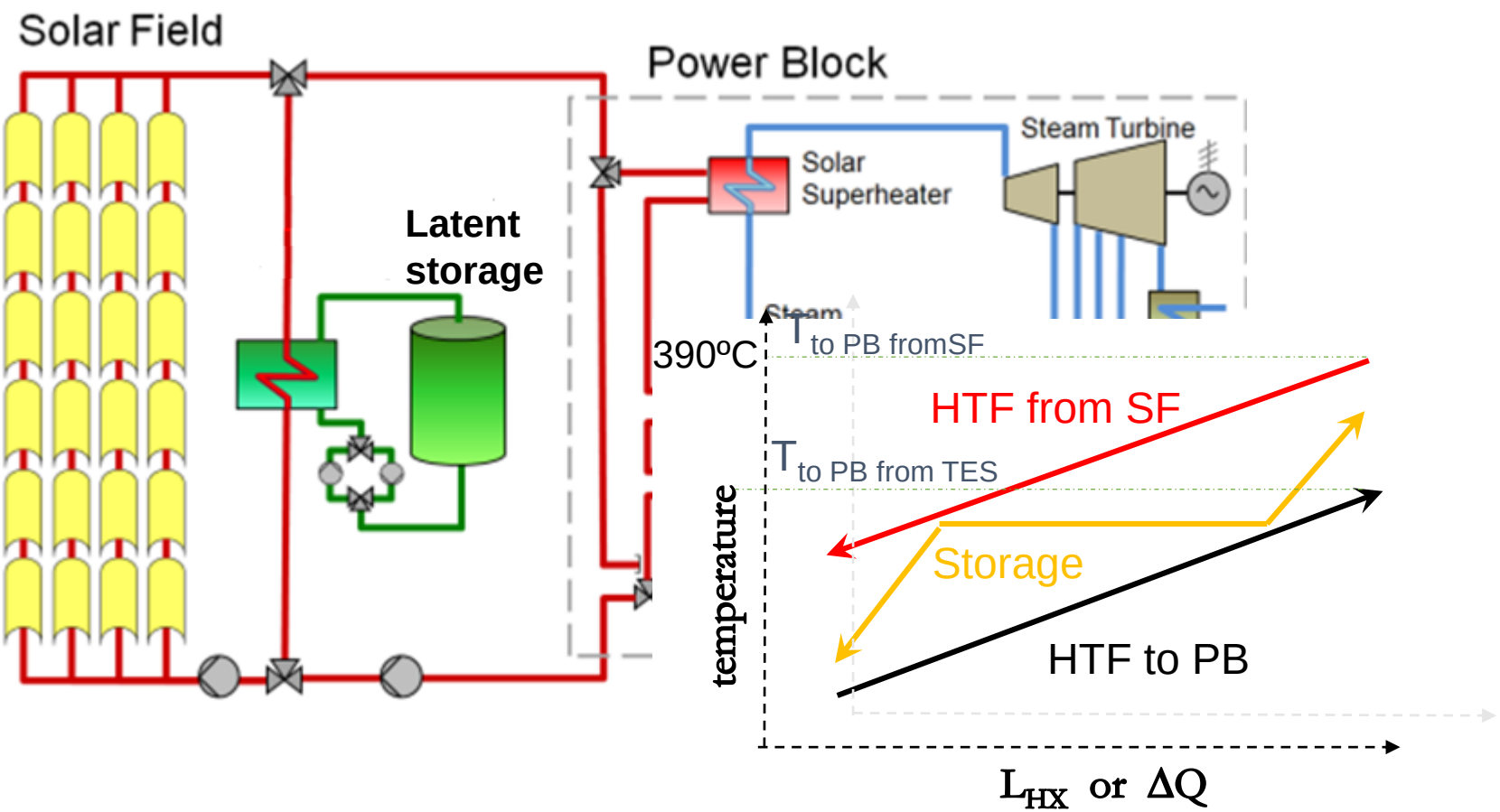
Discharge



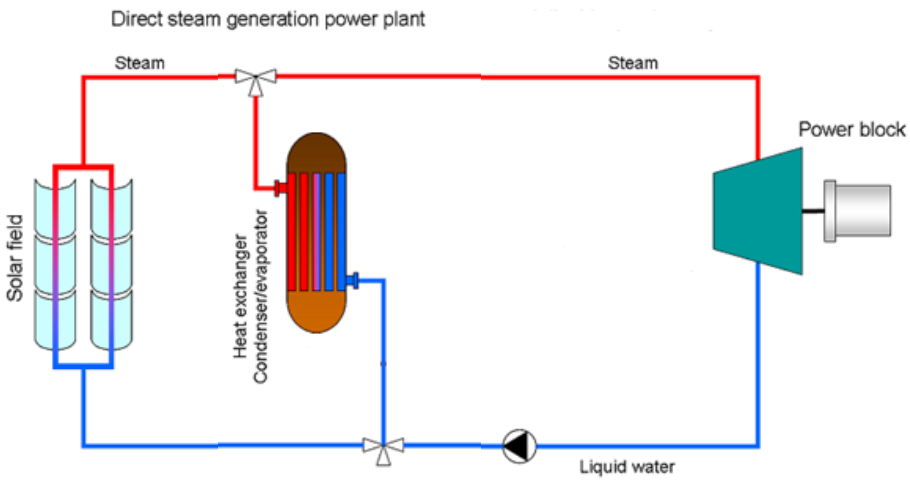


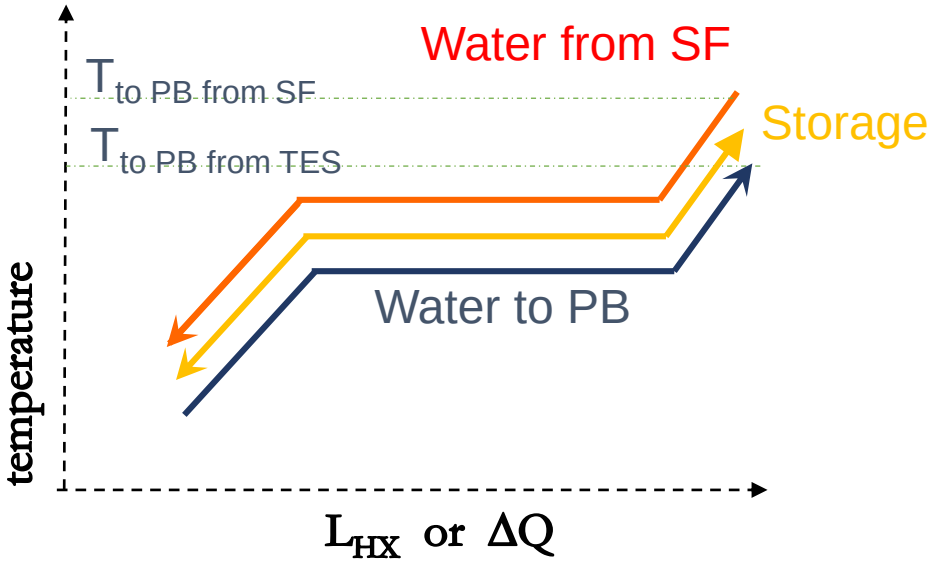


Is a Andasol type STE plant appropriate for a latent storage system? (III)



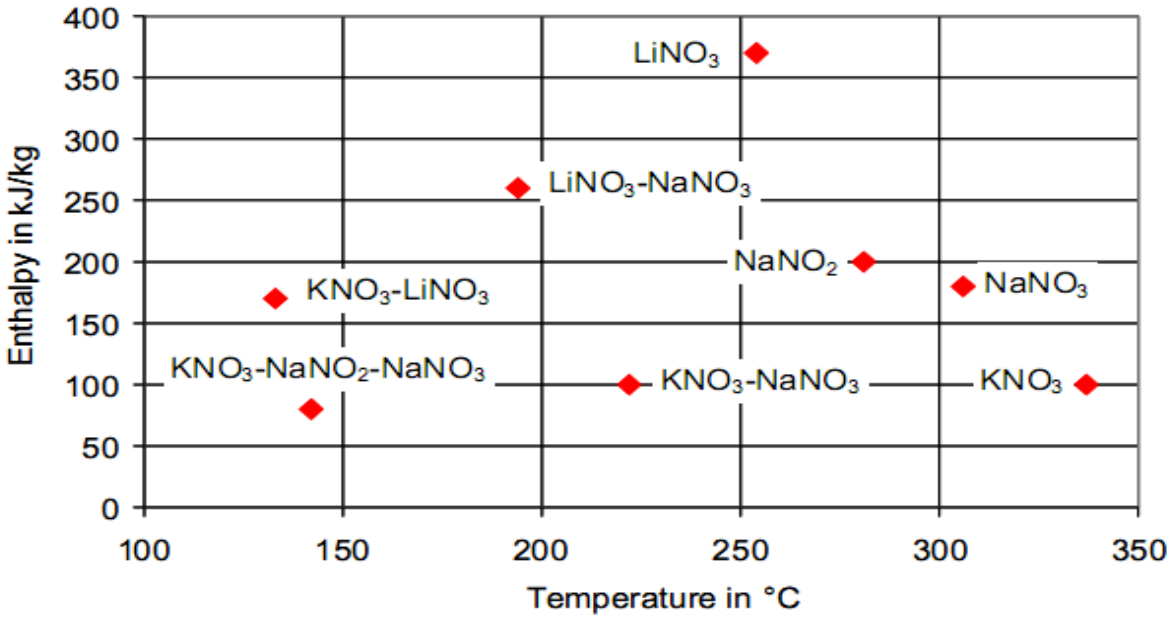
Direct Steam Generation STE Plant





T_{phase} suitable for DSG STE plants

- for parabolic troughs, T_{phase} should be of about 310ºC (~100bar)
- For towers, T_{phase} should be in the range 310-350ºC (~100-155bar)



Commercial STE plants with DSG

Tower

http://www.abengoasolar.com/

Tower: PS10 and PS20

- Sanlúcar la Mayor (Sevilla)
- Abengoa Solar
- 10/20 MWe
- **HTF: water liquid/vapor (240ºC)**
- **Storage: 1 h ⇨ RUTHS ACCUMULATOR**

Fresnel: Puerto Errado 1 & 2

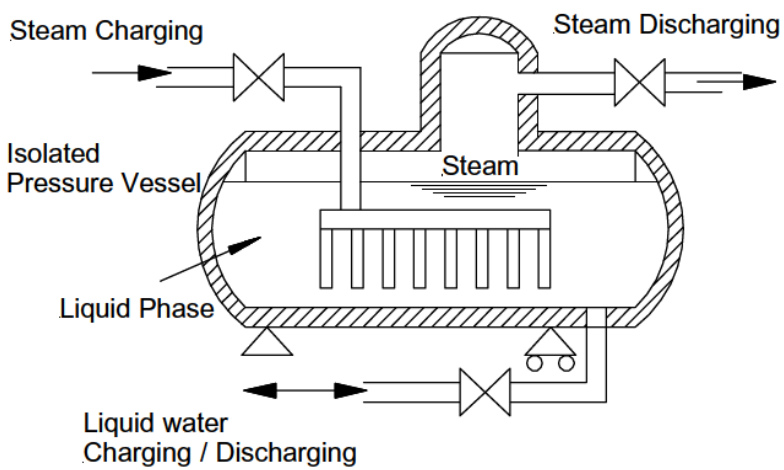
- Calasparra (Murcia)
- Novatec Solar España S.L.
- 1.4/30 MWe
- **HTF: water liquid/vapor (140-270ºC)**
- **Storage: 0,5 h ⇨ RUTHS ACCUMULATOR**

Fresnel

http://www.novatecsolar.com

Termal storage with steam accumulators

- Water as storage medium
- Use **sensible** heat storage in pressurized saturated liquid water
  - ⇨ Take advantage of the high volumetric heat capacity of water: 4200 kJ/m^{3}K
- Sliding pressure systems: **Ruths** accumulators (American patent 1929)
- **Charge**: Superheated or saturated steam is stored as saturated water ⇨ pressure, temperature and water mass increases in the vessel
- **Discharge**: Saturated steam is produced by lowering the pressure inside the storage vessel



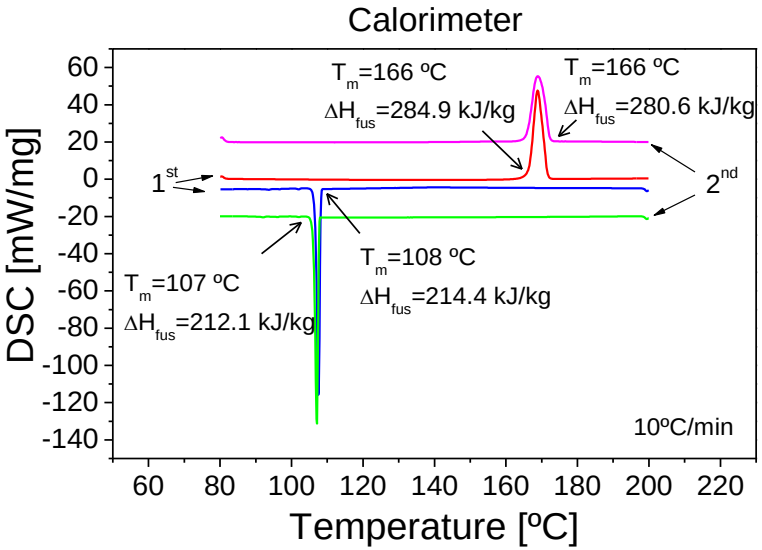
☺ Facilitate the operation of DSG plants under solar radiation transients

😐 Turbine has to work at lower pressure conditions (“sliding pressure”)

☹ They are not a long term storage option

Features of a good Phase Change Material (PCM)

- Adequate phase change temperature: T_{phase}
- No degradation in the working temperature range
- Stability under cycling
- Reversible process: low supercooling
- High phase change enthalpy: $\Delta H_{PhaseChange}$
- solid/liquid & liquid-solid phase changes:
  - Conduction is the main heat transfer mechanism =>**High thermal conductivity**

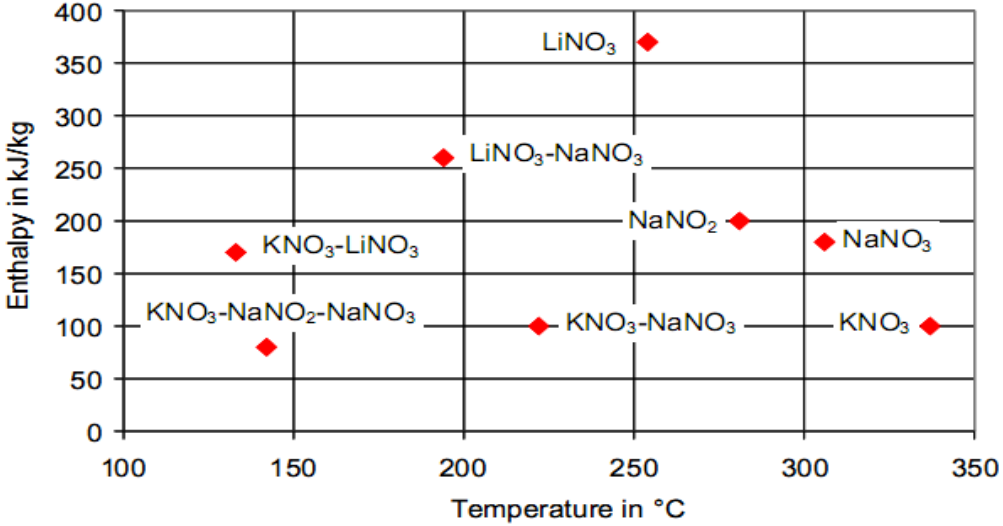


Heating peak: 166ºC
Cooling Peak: 107 ºC
60ºC supercooling!!!

D-Mannitol

Possible Phase Change Materials (PCM)

- **INORGANIC salts**



Thermal conductivity

<1W/mK

High thermal resistance

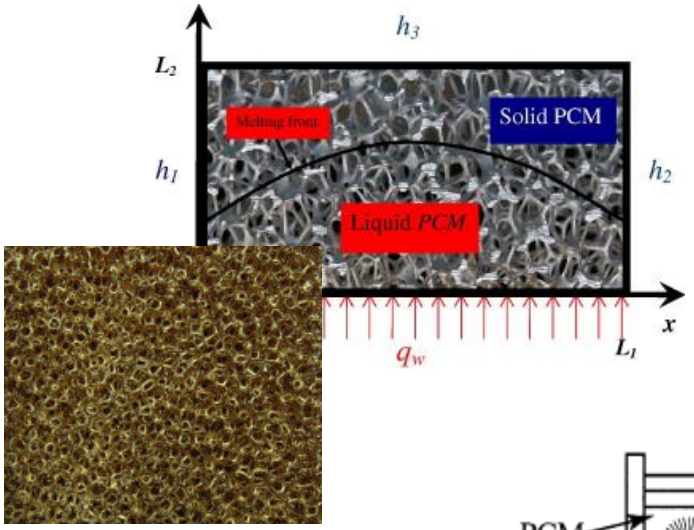
Since inorganic salt can´t be in direct contact with steam, they must be separated by walls, which must withstand the high pressure of the steam.

Solidification of the PCM in contact with these walls creates a thermal barrier for heat conduction (a great problem) because convection is avoided.

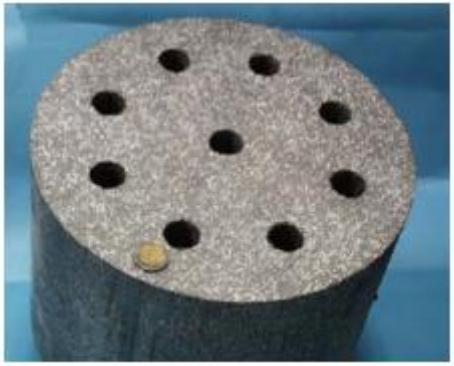
Reducing thermal resistance (I)

- **Packing the PCM in a matrix with high *k***

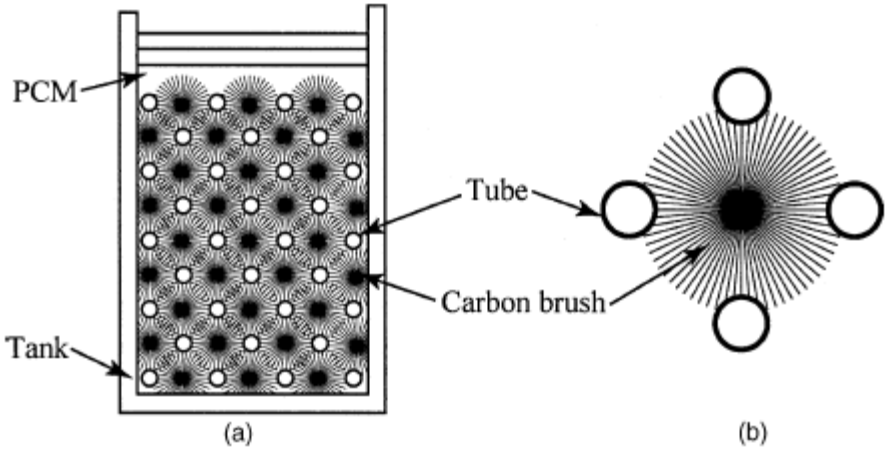
Metal foams



Composites: Graphite+salt



Carbon fibers

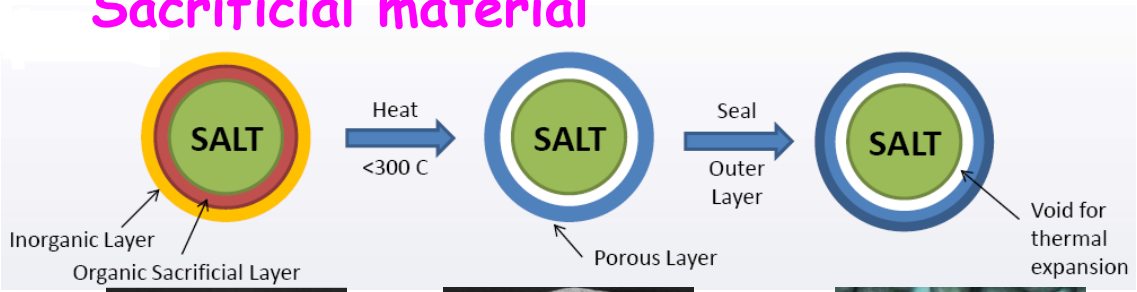


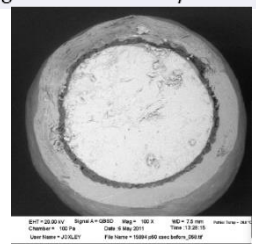
Reducing thermal resistance (II)

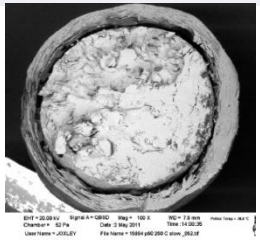
- **Macroencapsulation**

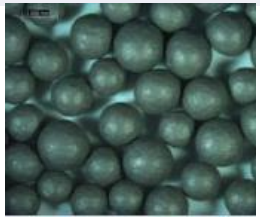
Metallic shells

Clay & Metal Shell & Sacrificial material









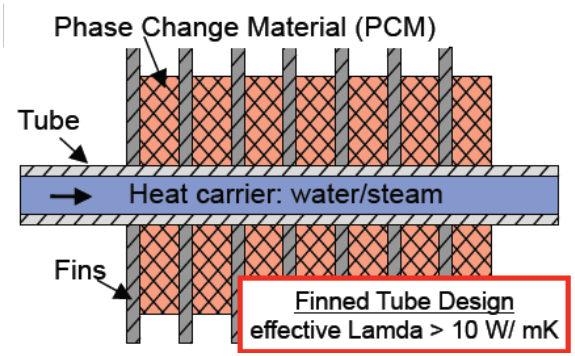
Porous PCM pellets & coating

Additional Problems:
- **ΔV/V high**
- **corrosión**

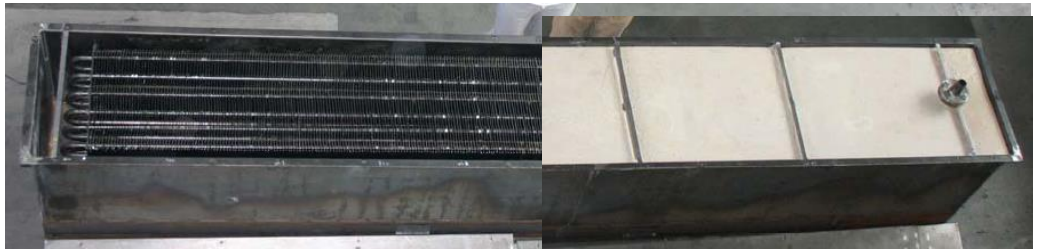
(*) Courtesy of Terrafore

Reducing thermal resistance (III)

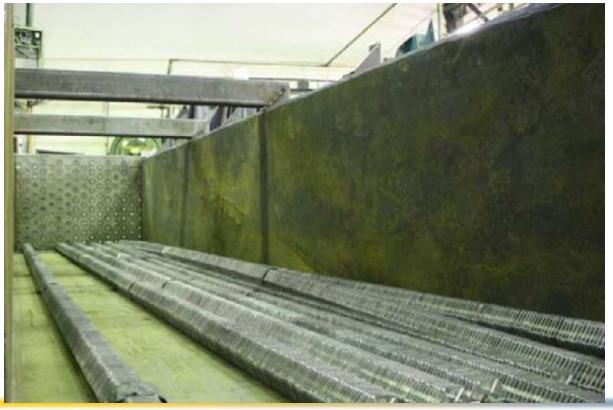
Extended Surfaces



Graphite foils (horizontal pipes)



Aluminium fins (vertical pipes)

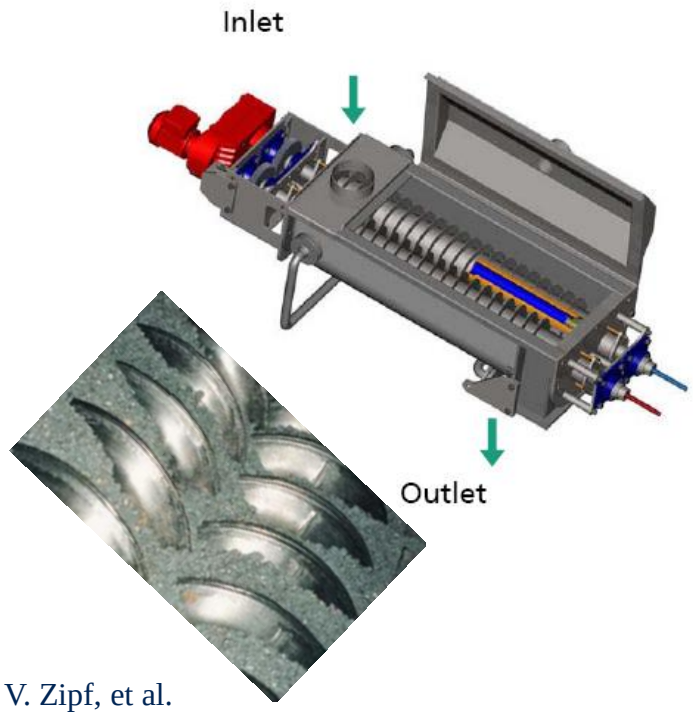


Extruded longitudinal fins

680 kWh

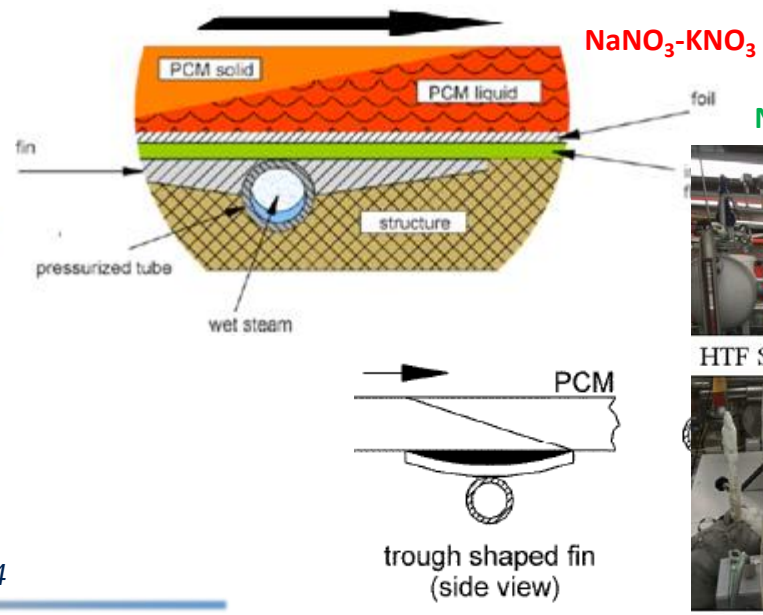
Latent heat storage: moving PCM
decoupling heat transfer area and storage place

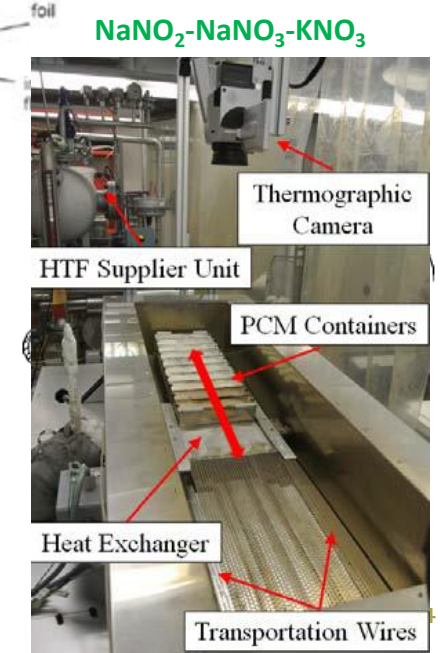
- **Innolat Project : Fraunhofer ISE**
  - Screw heat exchanger
  - Both heat and material transport
  - Self-cleaning



V. Zipf, et al.
Applied Energy DOI: 10.1016/j.apenergy.2012.11.044

- **PCMflux concept: DLR**
  - Thin liquid layer connects PCM and HTF piping
  - eutectic mixture NaNO2-NaNO3 & Tin as candidates for thin liquid layer
  - Self-cleaning

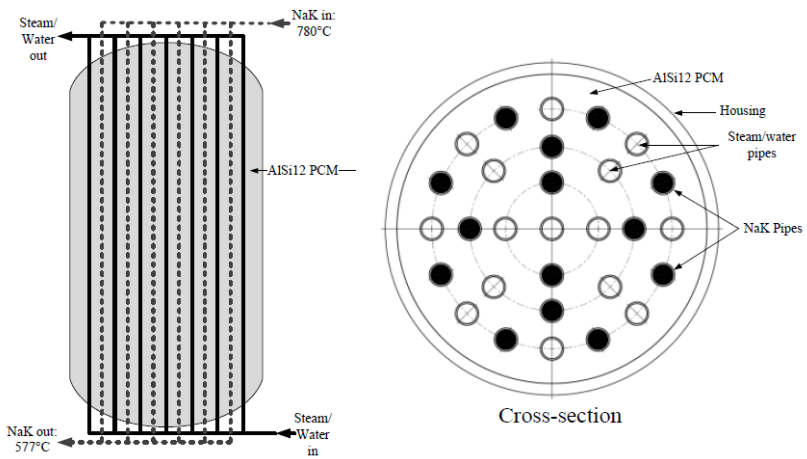




Possible Phase Change Materials (PCM)

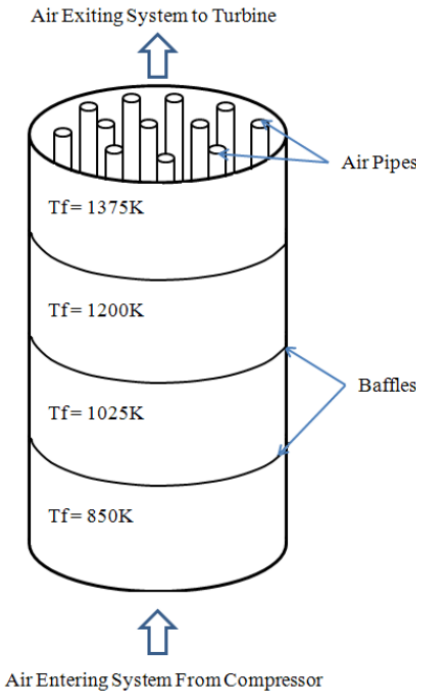
METALLIC alloys:

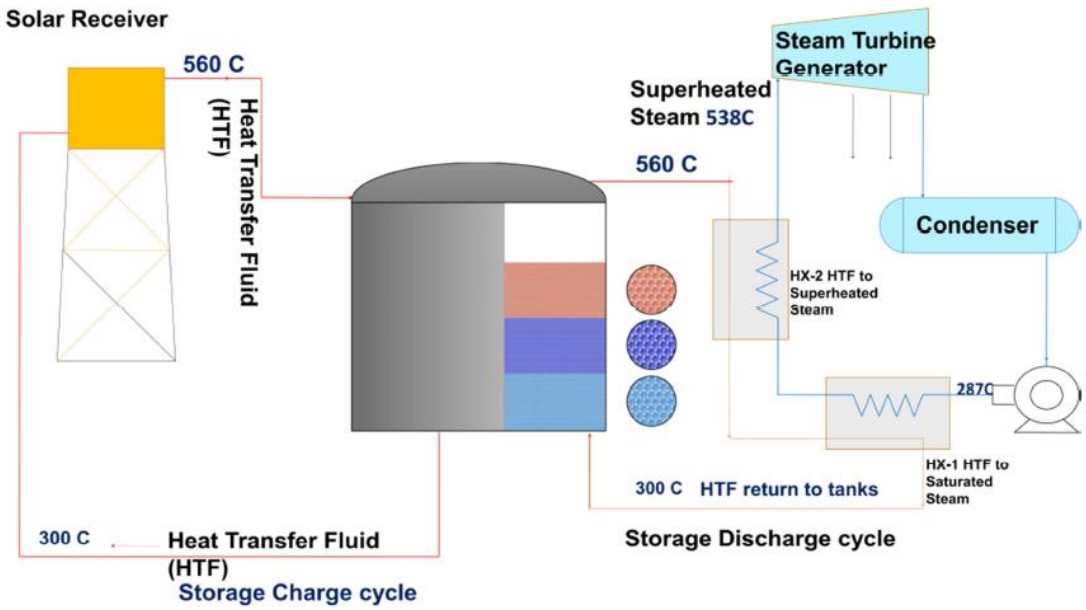
- Mg (49%)-Zn(51%): Tm=340ºC ; 138 - 180 kJ/kg
- Al(60%) – Mg(34%) – Zn (6%): Tm=450ºC , non stable?
- Mg (22%)-Zn(45%)-Cu(32%): Tm=305ºC ; 157kJ/kg (Tecnalia)



Further applications of latent storage

Substitution of a sensible TES by a cascade latent TES

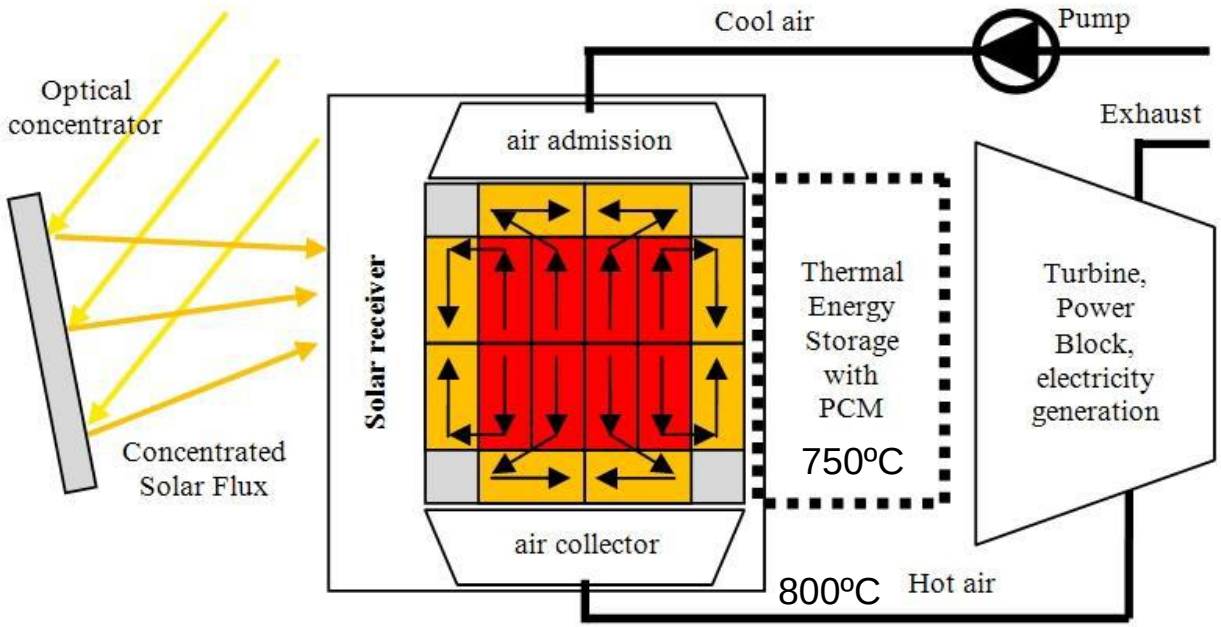




Further applications of latent storage (II)

Receivers protection

PCM: Li_2CO_3 +Copper for enhancing thermal conductivity



Verdier, et al.
SolarPACES2013

…final comments..

- STE provides dispatchable power thanks to large capacity storages available today commercially (two-tank configuration with molten solar salt as storage medium)
- There is a lot of room for reducing the cost of this type of systems (sensible TES): thermoclines –with/without fillers-, solids, etc.
- There is still a lot of work to do to provide complete TES solutions to STE plant with Direct Steam Generation (DSG)
- **Follow a holistic approach when studying TES**

Solar Facilities for the European Research Area

SFERA-III
1st Summer School
September, 9th- 10th, 2019
CNRS- PROMES, Odeillo, France

TES for solar thermal power plants

Questions ?

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