Heat Transfer Fluids and Thermal Energy Storage for CSP

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Thermal Energy Storage: one of the major distinctive advantage of CSP before other Renewable Energies

To resume:
HTF and TES are the interface between the solar E input and the PB.
HTF and TES: some of the current worldwide key priorities for CSP

CONCENTRATING SOLAR POWER ROADMAP

Decreasing cost and increasing production

Key findings

- By 2050, with appropriate support, CSP could provide 11.3% of global electricity, with 9.6% from solar power and 1.7% from backup fuels (fossil fuels or biomass).
- In the sunniest countries, CSP can be expected to become a competitive source of bulk power in peak and intermediate loads by 2020, and of base-load power by 2025 to 2030.
- The possibility of integrated thermal storage is an important feature of CSP plants, and virtually all of them have fuel-power backup capacity. Thus, CSP offers firm, flexible electrical production capacity to utilities and grid operators while also enabling effective management of a greater share of variable energy from other renewable sources (e.g. photovoltaic and wind power).
- This roadmap envisions North America as the largest producing and consuming region for CSP electricity, followed by Africa, India and the Middle East. Northern Africa has the potential to be a large exporter (mainly to Europe) as its high solar resource largely compensates for the additional cost of long transmission lines.

- CSP can also produce significant amounts of high-temperature heat for industrial processes, and in particular can help meet growing demand for water desalination in arid countries.
- Given the arid/semi-arid nature of environments that are well-suited for CSP, a key challenge is accessing the cooling water needed for CSP plants. Dry or hybrid dry/wet cooling can be used in areas with limited water resources.
- The main limitation to expansion of CSP plants is not the availability of areas suitable for power production, but the distance between these areas and many large consumption centres. This roadmap examines technologies that address this challenge through efficient, long-distance electricity transportation.
- CSP facilities could begin providing competitive solar-only or solar-enhanced gaseous or liquid fuels by 2030. By 2050, CSP could produce enough solar hydrogen to displace 3% of global natural gas consumption, and nearly 3% of the global consumption of liquid fuels.
HTF and TES: some of the current worldwide key priorities for CSP

Key actions in the next ten years

Concerted action by all stakeholders is critical to realising the vision laid out in this roadmap.

**Governments**
- Ensure long-term funding for additional RDD&D in all main CSP technologies; all component parts and all applications at all scales.
- Facilitate the development of ground and satellite measurement/modelling of global solar resources.
- Support CSP development through solar-specific incentives. These could include any combination of feed-in tariffs or premiums, binding renewable energy portfolio standards with solar targets, capacity payments and fiscal incentives.
- Where appropriate, require state-controlled utilities to bid for CSP capacities.
- Avoid establishing arbitrary limitations on plant size and hybridisation ratios (but develop procedures to reward only the electricity deriving from solar energy, not the portion produced by burning backup fuels).
- Streamline procedures for obtaining permits for CSP plants and access lines.

**Industry**
- Pursue cost reduction potential for all systems through:
  - New components
  - New transfer fluids
  - Higher working temperatures
  - Mass production
- Pursue cost reduction potential of heliostat fields with immediate control loop from receivers and power blocks to address transients
- Further develop heat storage, in particular three-step storage systems for direct steam generation solar plants, whether LFR, troughs, or towers
- Further develop central receiver concepts, notably superheated steam, molten salts and air receivers
- Work collaboratively with turbine manufacturers to develop new turbines

**Utilities**
- Provide certainty to investors with long-term power purchase agreements or bidding procedures
- Reward firm capacities of CSP plants
- Facilitate grid access for CSP developers
- Participate actively in project development
Financial issues

Effects of TES on financial issues:

Increase in investment costs by the added TES and the increased size of the solar field.

The whole energy cost changes only marginally.

The main merit of the TES:

Not to reduce the cost of electricity
But increase in plant capacity factor and yearly electrical output
Supply of base-load power competing with fossil-fuel plants

Herrmann 2004
50 MW Andasol CSP
Oil / molten salt

Levelized electricity cost for trough plants with molten salt storage.
Environmental issues

<table>
<thead>
<tr>
<th>life cycle phase</th>
<th>plant system</th>
<th>GHG (g CO$_2eq$/kWh)</th>
<th>Green House Gaz Emissions</th>
<th>Water consumptions</th>
<th>Cumulative Energy demand</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>wet</td>
<td>dry</td>
<td>wet</td>
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<tr>
<td>manufacturing</td>
<td>HTF</td>
<td>21%</td>
<td>2.5</td>
<td>2.6</td>
<td>0.10</td>
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<tr>
<td></td>
<td>power plant</td>
<td>19%</td>
<td>1.9</td>
<td>2.4</td>
<td>0.076</td>
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<tr>
<td></td>
<td>solar field</td>
<td>4.6</td>
<td>2.4</td>
<td>4.8</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>TES</td>
<td>23%</td>
<td>2.7</td>
<td>2.8</td>
<td>0.15</td>
</tr>
<tr>
<td>construction</td>
<td>HTF</td>
<td>8%</td>
<td>0.14</td>
<td>0.15</td>
<td>0.0012</td>
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<td>0.19</td>
<td>0.21</td>
<td>0.0041</td>
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<td>0.77</td>
<td>0.81</td>
<td>0.022</td>
<td>0.023</td>
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<td></td>
<td>TES</td>
<td>38%</td>
<td>0.64</td>
<td>0.67</td>
<td>0.0054</td>
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<td>operation</td>
<td>HTF</td>
<td>22%</td>
<td>2.2</td>
<td>2.3</td>
<td>0.081</td>
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<td>6.2</td>
<td>6.9</td>
<td>4.0</td>
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<td>0.61</td>
<td>0.64</td>
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<td>TES</td>
<td>1%</td>
<td>0.99</td>
<td>1.03</td>
<td>0.029</td>
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<td>dismantling</td>
<td>HTF</td>
<td>15%</td>
<td>0.018</td>
<td>0.018</td>
<td>0.000079</td>
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<td>power plant</td>
<td>0.014</td>
<td>0.014</td>
<td>0.000062</td>
<td>0.000061</td>
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<tr>
<td></td>
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<td>0.090</td>
<td>0.088</td>
<td>0.00039</td>
<td>0.00038</td>
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<td>TES</td>
<td>1.6%</td>
<td>0.0019</td>
<td>0.0018</td>
<td>0.000080</td>
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<td>disposal</td>
<td>HTF</td>
<td>24%</td>
<td>0.50</td>
<td>0.52</td>
<td>0.00087</td>
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<tr>
<td></td>
<td>power plant</td>
<td>0.14</td>
<td>0.08</td>
<td>0.00021</td>
<td>0.00022</td>
</tr>
<tr>
<td></td>
<td>solar field</td>
<td>0.77</td>
<td>0.81</td>
<td>0.0013</td>
<td>0.0013</td>
</tr>
<tr>
<td></td>
<td>TES</td>
<td>32%</td>
<td>0.68</td>
<td>0.71</td>
<td>0.0048</td>
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</tbody>
</table>

GHG
HTF 5.36 (20.6%)
TES 5.01 (19.3%)

CED
HTF 0.092 (23%)
TES 0.072 (18%)

ANDASOL like
Trough CSP
103 MW

<table>
<thead>
<tr>
<th>life cycle phase</th>
<th>HTF: Therminol VP1 Solutia</th>
<th>TES: Mined nitrate salt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.3 h</td>
<td>9</td>
</tr>
</tbody>
</table>

J. J. Burkhardt, G. a Heath, and C. S. Turchi,
Life cycle assessment of a parabolic trough concentrating solar power plant and the impacts of key design alternatives.
About 60% of the solar salt are from mined nitrates from Chile, others are from chemical industry

Use of synthetic salt only increases the TES GHG content by 52%
Needs in analysis of the State of the art HTF and TES for identification of bottlenecks and possible innovative approaches.

LETS go Through Historical HTF and TES in CSP...

Some illustrative exemples ....
First Historical CSP molten salt techno. : Thémis France

Targasonne France
1982 1985
2.5 MWe
560°C

550tons of molten salt
as HTS and TESM
40 MWh 5h

Direct and active TES

Molten Salt:
Atm pressure
Highly stable
High operating T
Affordable
Mature techno
but rather high solid. T

Captage
Tour
Héliostats

Stockage
Bac chaud
Bac froid

Bloc électrique
Générateur de vapeur

2.500 kW
28%
Tv 430°C
Pv 40 bars

4 × 4 × 3.5
110 m²
9,000 kWth
Te 250°C
Ts 450°C
Solar One  USA: direct steam generation DSG tower CSP 1982 - 1988
Steam as primary HTF
TES using oil as HTF and a natural filler (rocks) TESM in the tank

Thermocline approach:
One unique stratified tank instead of two
30% in cost reduction before two-tank salt
Extensively studied by Sandia lab.

TES mode: indirect and passive

Heat exchanger steam/oil

In the thermocline TES unit:
thermal oil 4230 m³
4120 tons granit particles
2060 tons sand
244°C-304°C

Discharge through a steam producing unit gives steam at 274°C
Major failures at the receiver due to DSG
SOLAR TWO 12.4 Mwel
From Solar One
1996-1999 Barstow Californie
Molten salt: NaNO<sub>3</sub>/KNO<sub>3</sub>
Higher solid, T

Efficiencies:
- receiver: 88%
- storage: 97%
- steam cycle: 34%
- whole efficiency: 13.5%

TES mode:
Direct and active

History: first USA Tower-CSP pilot, second step

SOLAR TWO 12.4 Mwel
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Higher solid, T

Efficiencies:
- receiver: 88%
- storage: 97%
- steam cycle: 34%
- whole efficiency: 13.5%

TES mode:
Direct and active

42 MWth
430 kW/m<sup>2</sup>
24 panels of 32 tubes
Tubes:
- 316 stainless steel
- 2.1 cm diam
- 1.2 mm wall
Pyromark paint 95%abs
TES is not only a TESM but also:
- Tanks
- Pumps
- Tubings
- Heating elements
- Insulations
- Fundations

<table>
<thead>
<tr>
<th>Thermal Capacity</th>
<th>110 MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molten Salt Inventory</td>
<td>1400 tonnes</td>
</tr>
<tr>
<td>Tank Design Standard</td>
<td>American Petroleum Institute 650</td>
</tr>
<tr>
<td>Tank Type</td>
<td>Field-erected, insulated, vertical, cylindrical tank with domed roof</td>
</tr>
<tr>
<td>Nominal Operating Temperatures</td>
<td></td>
</tr>
<tr>
<td>Cold Tank</td>
<td>290°C</td>
</tr>
<tr>
<td>Hot Tank</td>
<td>565°C</td>
</tr>
<tr>
<td>Diameters and Heights</td>
<td></td>
</tr>
<tr>
<td>Cold Tank</td>
<td>11.6 m diameter; 7.8 m high</td>
</tr>
<tr>
<td>Hot Tank</td>
<td>11.6 m diameter; 8.4 m high</td>
</tr>
<tr>
<td>Receiver Sump</td>
<td>4.3 m diameter; 3.4 m high</td>
</tr>
<tr>
<td>Steam Generator System</td>
<td>4.3 m diameter; 2.4 m high</td>
</tr>
<tr>
<td>Materials</td>
<td></td>
</tr>
<tr>
<td>Cold Tank</td>
<td>ASTM A516-70 carbon steel</td>
</tr>
<tr>
<td>Hot Tank</td>
<td>304 stainless steel</td>
</tr>
<tr>
<td>Tank Manufacturer</td>
<td>Pitt Des Moines</td>
</tr>
</tbody>
</table>

Insulation:
- 30 cm rockwool fibers
- + 5 cm glass fibers
- + Alu covers

Insulation:
- 46 cm rockwool fibers
- + 5 cm glass fibers
- + Alu covers

897 m³
834 m³

Hot tank: 565 °C; 11.6 m diameter; 8.5 m height; ASTM A 240, Grade 316N stainless steel; largest tank built at this temperature

Cold tank: 288 °C; 11.6 m diameter; 7.9 m height; ASTM A 516, Grade 70 carbon steel

+ 3 × 25 kWe soaked heating elements
History: first USA Tower-CSP pilot, second step

Molten salt inventory

1380 tonnes of nitrate salt awaiting melting at Solar Two.

TES is also concerned by material Handling and pretreatments

16 days needed for first melting

Conveyor belt feeding crushed salt from the hammer mill into the salt hopper.
Oil as heat transfer fluid and TESM

1999 at SEGS I II

SEGS I Daggett California
14 MWe - 1985
Trough CSP with mineral oil Caloria

TES: 3h direct and active mode
Two-Tank, oil only
cold 240°C 4160 m³/hot 307°C 4540 m³
Invest. cost 25 USD/kWhth (24% tanks, 42%oil)

Major fire and the end of oil based TES
ANDASOL Granada Spain 2009: today’s « standard » for trough CSP

- 50 MWe - 7.5 h storage (28 000 t molten salt binary nitrate)
- 625 collectors (12m length, 6m aperture) HTF solar oil
- A mix between SEGS and Themis/Solar Two

**TES mode:** indirect and active

**Oil:** High operating P

Limiting highest T

Flammable

15/12/2009

195 hectares

152 000 tonnes CO\(_2\)/an

50 MWe - 7.5 h storage (28 000 t molten salt binary nitrate)

625 collectors (12m length, 6m aperture) HTF solar oil

A mix between SEGS and Themis/Solar Two

Oil:

High operating P

Limiting highest T

Flammable

15/12/2009

2. ALMACENAMIENTO TERMICO.

- Dos tanques de almacenamiento de sales (φ = 36 m, h = 14 m)
- Fluido: 60% NaNO\(_3\), 40% KNO\(_3\)
- Cantidad: 28,500 t
- Temperatura de fusión: 221° C
- Rango de trabajo: 291° C - 384° C.
- Modo de operación: tanque frío/tanque caliente
- Capacidad de almacenamiento (Ei): 1010 MWh
- Capacidad de almacenamiento (h): 7.5 h @ 50 MW
- Bombas verticales e intercambiadores sales/fluido térmico
- Aprovechamiento energía máxima insolación
- Gestionabilidad
Today: the first industrial Solar CSP Tower

PS10 (Sevilla)

TES mode:
Direct and active
Mature but low capacity
expensive

Steam buffer storage
20-30 kWh/m³
100 €/kWh

PS10 Sevilla 11 MWe

Storage capacity 50 mn at 50%:
25 MWh steam 40 bars 250°C
Today: the first industrial 24h/day Solar CSP Tower

Gemasolar 2011: 15h of TES
20 Mwe
$T_{max} = 565^\circ C$
Next Crescent Dune USA 110 MWe
Limitations, alternatives and perspectives

For both HTF and TESM

Increasing $T$ limits in both low and high $T$
Maximizing heat transfer properties
Enhancing compatibility between HTF/TESM and containing materials
Increasing life time expectancy under thermal cycling
Reducing LCA impacts
Reducing investment costs

NEEDS in NEW HTF

Low vapor pressure avoiding expensive pressure-rated tanks
Exploring new fluid approaches (with nanoparticles, dense gas/particle suspensions,...)

NEEDS in NEW TESM

Exploring other TES technos. (Latent heat, thermochemical, compressed air)
Reducing investment costs
Reducing LCA impacts

NUMEROUS issues ... only some illustrative exemples for today in the following slides
Alternative fluids:

- Water steam in SF
- Eco-friendly oil (organic)
- Other molten salt
- Gaz (hot air, CO$_2$)

Enhanced molten salt (nanoparticles,...)
Dense gaz-particle suspensions

The temperature range is 160 °C to 210 °C

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Flashpoint</th>
<th>Density (20°C)</th>
<th>Cp (25°C)</th>
<th>Cp (200°C)</th>
<th>k (25°C)</th>
<th>k (200°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapeseed</td>
<td>285°C</td>
<td>920 kg/m$^3$</td>
<td>2001.6</td>
<td>2682.8</td>
<td>2015.8</td>
<td>2623.3</td>
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<tr>
<td>Sunflower</td>
<td>316°C</td>
<td>925 kg/m$^3$</td>
<td>1989.7</td>
<td>2620.1</td>
<td>2205.5</td>
<td>2690.1</td>
</tr>
<tr>
<td>Soybean</td>
<td>330°C</td>
<td>920 kg/m$^3$</td>
<td>2015.8</td>
<td>2623.3</td>
<td>2205.5</td>
<td>2690.1</td>
</tr>
<tr>
<td>Coconut</td>
<td>230°C</td>
<td>915 kg/m$^3$</td>
<td>2002.1</td>
<td>2534.3</td>
<td>2205.5</td>
<td>2690.1</td>
</tr>
<tr>
<td>Cotton</td>
<td>243°C</td>
<td>921 kg/m$^3$</td>
<td>2039.6</td>
<td>2509</td>
<td>2205.5</td>
<td>2690.1</td>
</tr>
<tr>
<td>Jatropha</td>
<td>236°C</td>
<td>920 kg/m$^3$</td>
<td>2015.8</td>
<td>2623.3</td>
<td>2205.5</td>
<td>2690.1</td>
</tr>
</tbody>
</table>

J.F. Hoffmann
AQYLON PROMES
The Natural Nitrates from Chile to keep as HTF but not as TESM

Before CSP needs:
9 to 21 Mt/year of nitrates!

133 Mm$^3$ wastes
417 km$^2$ polluted surface
> 100 ghost plants (P. Marr 2007)

About 800 €/t

The Natural Nitrates from Chile to keep as HTF but not as TESM

133 Mm$^3$ wastes
417 km$^2$ polluted surface
> 100 ghost plants (P. Marr 2007)
Air as HTF in solar trough CSP and TES on packed bed of rocks

ETH Zurich, plant Morocco

pilot-scale thermal storage prototype built and tested in Biasca, Switzerland.

Thermal behaviour of natural minerals

Needs in stabilization

Thermal Analysis (DSC): Setsys Cetaram

- **Si$_2$O$_5$Al$_2$(OH)$_4$** (Kaolinite)
- **500 - 600°C** Al$_2$O$_3$.2 SiO$_2$ (MetaKaolinite)
- **980°C** Al$_2$O$_4$Si (Spinel)
- **3Al$_2$O$_3$.2 SiO$_2$** (Mullite)
- **1400°C** Melting

Deshydration, deshydroxylation, hematite
Developed by the DLR

Advantages

- Low cost of the TESM,
- Easy manufacturing,
- High availability,
- Modular and simple system,
- High potential with PCM for DSG plants

Drawbacks

- Limited operating temperature
- Life time expectancy
- First heating step (water departure)
- Embodied Heat Transfer Exchanger
Sensible heat TES over solid media: concrete for CSP

Fig. 7. Temperatures and vapor pressure during start-up.
Sensible heat TES over solid media: concrete for CSP

Simulation ANDASOL 50 MWe

Photo: Solar Millenium AG
ASBESTOS Containing Wastes (ACW):
174 Mt of Asbestos used during the XX century worldwide

MUNICIPAL SOLID WASTES
INCINERATORS
FLY ASHE
EU(15): 1.6 Mt/year

COAL-FIRED
POWER PLANTS
FLY ASHE
750 Mt/y World
EU(15) 42 Mt/year

METALURGIC SLAGS
Steel > 411 Mt/y World
Copper > 25 Mt/y
Asbestos Containing Wastes (ACW) and Fly Ashes Wastes (FAW)

**Cost of treatment**: 1200 euros/t paid by the ACW owner

**Landfill disposal**: 150 to 750 euros/t

**Embodied E & GHG payback**: one year of new use in CSP

**Commercial price**: 8–10 euros/tonne
THERMAL BEHAVIOURS ACW
(same for CFA)

70% pyroxènes
30% Wollastonite - Akermanite

from glass

from ceramics
STORAGE CAPACITIES

ACW ceramics

$\rho = 3100 \text{ kg/m}^3$

FAW ceramics

$\rho = 2975 \text{ kg/m}^3$

- Cp (J/kg K) vs. $T$ (°C)
- Storage capacities:
  - ACW ceramics: 800 - 1034 J/(kg K)
  - FAW ceramics: 785 - 1072 J/(kg K)
THERMAL
CONDUCTIVITIES

$\lambda \approx 1.5 \text{ W/(m K)}$

ACW ceramics

FAW ceramics

NETZSCH model DSC 404 C Pegasus
EMBODIED ENERGY PAY-BACK TIME

Mass yield: 14-26%
E efficiency: 35-56%

\[ \Delta H = \int_{20}^{1400} C_p(T) \,dT + \Delta H_m \]

1.64x10^3 J/g

\[ \Delta H_{\text{ind}} = 33.5 \text{ MJ/kg} \]

<table>
<thead>
<tr>
<th>Process</th>
<th>Lowest T °C</th>
<th>Highest T °C</th>
<th>Daily cycle Nb</th>
<th>( E_c/E_m ) ratio</th>
<th>Payback Nb cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSP trough</td>
<td>250</td>
<td>390</td>
<td>1</td>
<td>49</td>
<td>261 x 3</td>
</tr>
<tr>
<td>CSP air tower</td>
<td>400</td>
<td>800</td>
<td>1</td>
<td>153</td>
<td>84 x 3</td>
</tr>
<tr>
<td>A CAES</td>
<td>60</td>
<td>650</td>
<td>3</td>
<td>625</td>
<td>61 x 3</td>
</tr>
</tbody>
</table>

PB efficiency: 33%
Pay-back time: 2 months to 2 years
Sensible Heat
Thermal Energy Storage Materials
for CSP

<table>
<thead>
<tr>
<th>Materials</th>
<th>HT concrete</th>
<th>molten salts</th>
<th>HT Ceramics</th>
<th>ACW ceramics</th>
<th>FAW ceramics</th>
</tr>
</thead>
<tbody>
<tr>
<td>density [kg/m³]</td>
<td>2750</td>
<td>900 - 2600</td>
<td>3500</td>
<td>3120</td>
<td>2975</td>
</tr>
<tr>
<td>Cp [J/(kg×K)]</td>
<td>916</td>
<td>1500</td>
<td>866</td>
<td>800 - 1034</td>
<td>714 - 1122</td>
</tr>
<tr>
<td>ρ×Cp [kJ/(m³×K)]</td>
<td>2519</td>
<td>1350 - 3900</td>
<td>3031</td>
<td>2496 - 3226</td>
<td>2124 - 3338</td>
</tr>
<tr>
<td>λ [W/(m×K)]</td>
<td>1.0</td>
<td>~ 0.15 – 2.00</td>
<td>1.35</td>
<td>2.1 – 1.4</td>
<td>1.16 – 1.59</td>
</tr>
<tr>
<td>coeff. of thermal expansion [10⁻⁶/K]</td>
<td>9.3</td>
<td>---</td>
<td>11.8</td>
<td>8.8</td>
<td>8.7</td>
</tr>
<tr>
<td>price [euros/tonne]</td>
<td>80</td>
<td>500 - 750</td>
<td>4500 - 9000</td>
<td>8 - 10</td>
<td>10 to 1200</td>
</tr>
</tbody>
</table>
Thermal fatigue and thermal shocks

under air
500 – 1000°C
100 – 2500°C/min

Fatigue tests
Thermal shocks
α measurements

d = 25 mm
L = 200 mm

Surface T
10 mm
25 mm
40 mm

dT/dt = 100 °C/min
dT/dt = 300 °C/min
dT/dt = 2500 °C/min
REFRACTORY BEHAVIOR: Ultrasonic echography study

ACW Ceramique

GEMH Limoges
Compatibility with CSP HTF

Thermal cycling under air 30 bars 610°C, 2500h
On ACW ceramic and CFA ceramic

In molten salts:
High compatibility of all recycled ceramics and nitrate
No compatibility with other salt (sulfate, carbonate, phosphate)
Sensible heat

Latent heat

L/S domain

Phase rule: \( w = C - r + 2 - \varphi \)

C number of components, r number of reaction, \( \varphi \) number of involved phases
Numerous PCMs In the T Range of CSP

<table>
<thead>
<tr>
<th>Material</th>
<th>Storage type</th>
<th>Number of cycles/hours tested</th>
<th>Temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 wt% Al/34% Mg/6% Zn alloy</td>
<td>Latent</td>
<td>1000 thermal cycles</td>
<td>25–550</td>
</tr>
<tr>
<td>50 mol% NaNO$_3$/KNO$_3$</td>
<td>Latent</td>
<td>&gt;100 thermal cycles</td>
<td>175–275</td>
</tr>
<tr>
<td>Sodium nitrate</td>
<td>Latent</td>
<td>2600 h</td>
<td>350</td>
</tr>
<tr>
<td>LiKCO$_3$ (intermediate compound of 35 wt% Li$_2$CO$_3$/65% K$_2$CO$_3$ mixture)</td>
<td>Latent</td>
<td>5650 h/129 cycles</td>
<td>430–535</td>
</tr>
<tr>
<td>18.5 mol% NaNO$_3$–81.5% NaOH</td>
<td>Latent</td>
<td>1000 cycles</td>
<td>230–300</td>
</tr>
<tr>
<td>Li$_2$CO$_3$</td>
<td>Latent</td>
<td>408 h/13 cycles</td>
<td>676–776</td>
</tr>
<tr>
<td>Na$_2$CO$_3$</td>
<td>Latent</td>
<td>288 h/21 cycles</td>
<td>808–908</td>
</tr>
<tr>
<td>52.2 wt% BaCO$_3$–47.8% Na$_2$CO$_3$</td>
<td>Latent</td>
<td>984 h/36 cycles</td>
<td>636–736</td>
</tr>
<tr>
<td>81.3 wt% Na$_2$CO$_3$–18.7% K$_2$CO$_3$</td>
<td>Latent</td>
<td>1032 h/38 cycles</td>
<td>737–797</td>
</tr>
</tbody>
</table>

TES based on Latent Heat (PCM)

**Main advantages**

1. High storage capacity
2. Self regulated temperature
3. Modular system
4. Wide possible working temperature range

**Main disadvantages**

1. Subcooling phenomena
2. Thermal conductivity
3. Corrosion
4. Thermique and chemical stability
5. Toxicity
6. Inflammability
7. Price
8. Disponibility

![Diagram](image.png)

 Thermal effect delayed by thermal diffusion
TES based on Latent Heat (PCM)

- Stockage chaleur Latente L/S
- Inorganic PCM
- Graphite /salt composites

50-500 kWh/m³ (ΔT≈ 0°C !)
~30 €/kWh
Fig. 1. Temperature-enthalpy characteristics for sensible heat storage systems with sensible heat transfer fluid in absorbers (left) and combined sensible/PCM storage for direct steam generation in absorbers (right). Sections in power block steam cycle: 1–2 preheating, 2–3 evaporation, 3–4 superheating.

Numerous innovative approaches but few mature ones
High potential of CSP enhancement
High potential of research and business

But:
Costly R&D tasks
Few involved people
Difficulties to find funding for large scale pilot
HTF and TES for CSP
A wide and wonderful research and industrial world
with still so much work to achieve !!!

Then, PhD students, we need you!