Synergies between nuclear and solar thermal energy

FISA 2019 Technical workshop “Cross-cutting fission, fusion and non-nuclear energy synergies, challenges and opportunities”
6.6.2019

Florian Sutter (DLR)
Contents

- Overview of Concentrated Solar Power Technology (CSP)
- State of the art: Molten Nitrate Salt Technology
- Pathways for next generation CSP plants
- Summary and Outlook
Solar Technologies: PV and CSP

Photovoltaics (PV)

- Sunlight
- $\eta \approx 18\%$ (multi-Si)
- Electricity

Concentrating Solar Power (CSP)

- Sunlight
- Heat
- $\eta \approx 14-20\%$ (solar to electric)
- Thermal Heat Storage
- Electricity
The value of thermal storage

- With increasing share of fluctuating sources in the grid, storage becomes necessary!
- CSP can follow demand curve and act as a complement to PV and wind, substantially increasing their penetration
- Thermal storage costs of 27 US$/kWh\text{th} (equivalent to 73 US$/kWh\text{el}) are at least 4 times more cost efficient than battery storage
- Unreached storage capacity up to 5 GWh\text{th} by batteries
- State of the art:
  - storage in molten nitrate salts (KNO$_3$-NaNO$_3$, 40-60 wt.-%)
  - Lifetime: 30 years, thermal losses: 1.8°C/day
  - ~7-12h storage, 2 tank system
    - 290°C / 400°C → 11 years commercial experience
    - 290°C / 565°C → 8 years commercial experience

![Chart 4: Solar Millennium AG, 7.7h storage, Andasol, Spain]

![10 hour storage, Crescent Dunes, Nevada]

FISA 2019, 6.6.2019, Pitesti, F. Sutter
Some facts about Concentrated Solar Power

- Installed capacity in 2006: 0.5 GW, in 2019: **5.5 GW**.
- Around 40% of the capacity is installed in Spain. The 50 plants represent around **3% of the Spanish electricity generation mix**.
- IEA forecast: CSP share in the electricity mix could reach about **4% in Europe and 11% worldwide by 2030**.
Cost of CSP

- Recent auction results suggest high learning rates. World record CSP lowest price is 6€/kWh for a 150 MW plant with 8 hours of thermal storage in Australia. 7€/kWh have been recently contracted in Dubai.

- PV prices are <3€/kWh. Installed PV capacity worldwide ~400GW (2017) → as much as nuclear → 80 times more than CSP

- Complementing PV/CSP plants (such as Morocco’s 800 MW Noor Midelt) are considered competitive to natural gas.

Levelized cost of electricity LCOE for projects 2010-2022

Source: IRENA Renewable Cost Database and Auctions Database.

Note: Each circle represents an individual project or an auction result where there was a single clearing price at auction. The centre of the circle is the value for the cost of each project on the Y axis. The thick lines are the global weighted average LCOE, or auction values, by year. For the LCOE data, the real WACC is 7.5% for OECD countries and China, and 10% for the rest of the world. The band represents the fossil fuel-fired power generation cost range.
Synergies between nuclear and CSP

Nuclear reactor is replaced by solar collector field and Thermal Energy Storage (TES)

Synergies:
• Power block
• Heat exchanger
• Heat transfer fluid
• Use of high temperature materials
• Testing and qualification methods
## Types of CSP solar collector fields

<table>
<thead>
<tr>
<th>Type</th>
<th>Parabolic Trough</th>
<th>Linear Fresnel</th>
<th>Solar Tower</th>
<th>Dish Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Line Focus</td>
<td>Line Focus</td>
<td>Point Focus</td>
<td>Point Focus</td>
</tr>
<tr>
<td>Tracking</td>
<td>1-axis</td>
<td>1-axis</td>
<td>2-axis</td>
<td>2-axis</td>
</tr>
<tr>
<td>Conc.</td>
<td>C ~ 80</td>
<td>C ~ &lt;80</td>
<td>C ~ 200 - 1000</td>
<td>C &gt; 1000</td>
</tr>
<tr>
<td>Temp.</td>
<td>200°C – 500°C</td>
<td>200°C – 500°C</td>
<td>500°C – 1200°C</td>
<td>700°C (Stirling)</td>
</tr>
<tr>
<td>Power</td>
<td>50 - 280 MW&lt;sub&gt;el&lt;/sub&gt;</td>
<td>50 - 280 MW&lt;sub&gt;el&lt;/sub&gt;</td>
<td>10 – 150 MW&lt;sub&gt;el&lt;/sub&gt;</td>
<td>0.003 – 0.025 MW&lt;sub&gt;el&lt;/sub&gt;</td>
</tr>
</tbody>
</table>
NOOR Ouarzazate Solar Complex (Morocco)

Parabolic trough 160 MW_{el}

Parabolic trough 200 MW_{el}

Solar tower 150 MW_{el}

Image: Sener
Parabolic trough technology

Absorber coating produced by sputtering processes
\( \alpha = 96\%, \ \varepsilon = 7.3\% \) (400ºC)
Stable up to 600ºC in vacuum

Vacuum

Glass tube with anti-reflective (AR) coating
\( \tau \approx 97\% \)

Image: Schott

Steam temperature limited to 400ºC due to employed heat transfer fluid
(e.g. Syltherm 800 or Therminol VP-1)

Development of thermo-oils with higher upper temperature limit (e.g. 425ºC with Wacker Heliosol 5a)

Direct steam (no storage)

Molten salt (up to 565ºC)
Molten salt solar towers

- Molten salt is displacing steam as state of the art heat transfer fluid
- Component efficiency and lifetime have a major impact on the levelized cost of electricity of the plant

Ni-base alloy
T_{film} = 600° C
Corrosion rate ~10µm/a in solar salt (40 wt-% KNO₃, 60 wt-% NaNO₃)

Pyromark 2500
ε₇₅₀° C = 82%
η_{250kW/m²,750° C} = 77%
Δαₜ = 2 %-/p/a
T_{skin} ≈ 750°C

Mirror weight: 10 kg/m²
Mirror cost: ~12 €/m²
Reflectance: ρ_{s,φ} = 94.5 %
Degradation: Δρ_{s,φ} = 0.5 %-/p/a

φ=4.7 mrad
φ=6-46 mrad

Top coat
Prime coat
Base coat
4mm glass
Cu
Outer surface of tubular receivers

Coating requirements

- Solar absorptance > 96%
- Low thermal emittance
- Skin temperature: up to 750°C
- High thermal conductivity
- Hot oxidation resistance
- Environmental corrosion resistance during night / plant shutdown

- Erosion resistance to dust and sand storms
- Chemical inertness to dust deposits (also at high temperature)
- Possibility for recoating on top of tower
- Possibility to cure paint coatings using solar energy
- Lifetime: up to 30 years

[Dish facility ceded by CIEMAT-PSA]
Inner surface of tubular receivers

Corrosion mechanisms:

- Cr-depletion
- Complex oxide scale formation
- Accelerated corrosion by oxides of decomposed salt

\[ \text{NO}_3^- (\text{liquid}) \leftrightarrow \text{NO}_2^- (\text{liquid}) + \frac{1}{2} \text{O}_2 (\text{gas}) \]

\[ a \text{NO}_2^- (\text{liquid}) + b \text{NO}_3^- (\text{liquid}) \leftrightarrow v \text{O}_2^- (\text{liquid}) + w \text{NO}_2 (\text{gas}) + x \text{NO}_3 (\text{gas}) + y \text{N}_2 (\text{gas}) + z \text{O}_2 (\text{gas}) \]

Annual corrosion rate [µm/ year] of different alloys in contact with solar salt (KNO$_3$-NaNO$_3$, 40-60wt.%)
Coatings for molten salt receivers

INTA and DECHEMA are developing aluminide and Cr-diffusion coatings for corrosion protection. Only negligible mass loss was detected on coated samples in contact with solar salt at 560 and 580°C for 10,000h.

- Minimum changes in coating thickness and surface Al-concentration for INTA coating
- DECHEMA coating experiences an initial mass loss (dissolution of Cr$_{23}$C$_6$ into the salt), then stable oxide scale (Cr-reservoir re-heals the oxide scale).

Static testing in solar salt at 580°C

INTA coating-substrate interdiffusion during testing at 580°C in solar salt

[A. Agüero, INTA, M. Galetz, DECHEMA, 2019]
Dynamic testing of corrosion in molten solar salt

Test facility for thermal energy storage in molten salts (TESIS) at DLR in Cologne, Germany

- Molten salt mass flow: 8 kg/s (1.97 m/s)
- 21 material types to be tested (116 samples)
- 500 cycles will be conducted (equivalent to approx. 1 year of operation)
- Testing will start this month
Further research topics related to molten solar salt

- Increase reliability of hot tank (565°C) to meet the 30 year lifetime target

- Improving lifetime of components (valves, gaskets, pumps)

- Operation at 600°C keeping salt degradation and within acceptable limits

- Consideration of occupational safety and environmental aspects (Cr-VI enrichment of salts, nitrogen oxide gas release)

- Development of thermocline molten salt tank technology

- Investigation of high energy density filler materials to increase energy density and reduce cost
Power block

• State of the art steam turbines for CSP:
  • large number of starts (daily)
  • rapid start-up
  • typical size of 50 – 250 MW, max. steam inlet: 180 bar / 565°C

• Water or air cooled condenser

• DoE has selected the supercritical carbon dioxide (sCO₂) Brayton cycle as the best-fit power cycle for increasing CSP system thermo-electric conversion efficiency. Target: 50%
  → temperatures >700°C are required
  → alternative HTF is required
Next generation CSP plants (Gen3)

- HTF with higher temperature range than Solar Salt is required to feed sCO₂ cycle

- First experiments with liquid sodium and solar towers were carried out in 1980s in USA and Spain.

- 1.1 MW_{el} pilot plant using sodium as HTF was commissioned in 2018 in Jemalong, Australia.

- 30 MW_{el} commercial plant is under development.

- H2020 NEXTOWER project: coupling a liquid lead storage system with an air-based CSP plant (up to 800ºC)
Next generation CSP plants (Gen3)

DEO identified 3 pathways, each of them containing substantial technological, economical or reliability risk

[Chart 19]

Molten Salt Pathway

- Most familiar approach (similar receiver design than current state of the art)
- Raising hot salt temperature to 720°C brings material challenges
- Selection of compatible high temperature molten salt and structural materials is needed
- Understanding of corrosion mechanisms in carbonate and chloride salts is needed
- Components like pumps and valves need to be developed

Possible salt candidates

<table>
<thead>
<tr>
<th>Salt System (Composition in wt%)</th>
<th>$T_m$ (°C)</th>
<th>$T_{max}$ (°C)</th>
<th>$H$ ($J g^{-1}$)</th>
<th>$c_p$ ($J g^{-1} K^{-1}$)</th>
<th>$\rho$ (g cm$^{-3}$)</th>
<th>$\rho \cdot c_p$ (J cm$^{-3}$ K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KNO$_3$-NaNO$_3$(solar) (40-60)</td>
<td>240$^b$</td>
<td>530-565</td>
<td>113</td>
<td>1.55$^a$</td>
<td>1.84$^a$</td>
<td>2.85$^a$</td>
</tr>
<tr>
<td>K$_2$CO$_3$-Li$_2$CO$_3$-Na$_2$CO$_3$ (35-32-33)</td>
<td>397</td>
<td>&gt;650</td>
<td>273</td>
<td>1.85$^a$</td>
<td>1.98$^a$</td>
<td>3.66$^a$</td>
</tr>
<tr>
<td>KCl-LiCl (55-45)</td>
<td>355</td>
<td>&gt;700</td>
<td>236</td>
<td>1.20$^a$</td>
<td>1.65$^e$</td>
<td>1.98$^e$</td>
</tr>
<tr>
<td>KCl-MgCl$_2$ (61-39)</td>
<td>426</td>
<td>&gt;700</td>
<td>355</td>
<td>1.15$^e$</td>
<td>1.92$^e$</td>
<td>2.22$^e$</td>
</tr>
<tr>
<td>NaF-NaBF$_4$ (3-97)</td>
<td>385</td>
<td>700</td>
<td>N/A</td>
<td>1.51$^e$</td>
<td>1.75$^e$</td>
<td>2.65$^e$</td>
</tr>
<tr>
<td>KF-ZrF$_4$ (32-68)</td>
<td>390</td>
<td>&gt;700</td>
<td>N/A</td>
<td>1.05$^e$</td>
<td>2.80$^e$</td>
<td>2.94$^e$</td>
</tr>
<tr>
<td>KF-LiF-NaF (59-29-12)</td>
<td>454</td>
<td>&gt;700</td>
<td>400</td>
<td>1.89$^e$</td>
<td>2.02$^e$</td>
<td>3.82$^e$</td>
</tr>
</tbody>
</table>

The table contains results from own measurements and literature values [6-17].
$^a$Values at 400°C.
$^b$Approximate liquidus temperature.
$^c$Values at 700°C.

[T. Bauer, DLR, Molten Salts Chemistry, 2013]
Falling Particle Pathway

Benefits:

• Direct absorption of particles - no need for expensive alloys, estimated cost reduction potential of 16% compared to Molten Salt Towers
• No freezing issues with particles
• No flux limits

Challenges:

• Efficient particle heating, flow control
• Particle attrition and erosion of metallic structures at elevated temperatures
• Particle to sCO$_2$ heat exchanger efficiency
Gas Phase Pathway

Benefits:
- Stability of HTF over temperature range → no freezing issues
- Inert interaction with pipes
- Minimal environmental and safety hazards

Challenges:
- Requires indirect storage (phase change material or particle storage)
- Power consumption for fluid circulation
- Gases have inferior heat transfer
- High cost and low stress resistance of high temperature alloys >700°C

Usage of stable gaseous HTF such as CO₂, Helium or Argon at ~75 bar
Summary

- CSP share in the energy mix is expected to grow in the coming years, providing flexibility to compensate fluctuating sources like PV or wind.

- The use of molten nitrates as Thermal Energy Storage and Heat Transfer Fluid (HTF) up to 565°C has become state of the art, although the technology needs further improvement (reliability, cost, higher temperature)

- The supercritical carbon dioxide (sCO2) Brayton cycle was identified as the best-fit power cycle for increasing CSP efficiency

- Promising HTFs to deliver >700°C for CSP Gen3 plants are: chloride molten salts, particles, gaseous energy carriers or liquid metals.
Outlook

- Workshop of H2020 project RAISELIFE on CSP materials with increased service lifetime to be held on 21st of November 2019 in Düsseldorf (information and registration soon available under www.raiselife.eu)

- Collaboration within future Horizon 2020 project proposals?
  - LC-SC3-RES-35-2020: Reduce the cost and increase performance and reliability of CSP plants
Thank you for your attention!

Florian.Sutter@dlr.de
Tel.: +34 950 277684

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