Advanced Concentrating Thermal Technologies for Power and Process Heat Generation

Robert Pitz-Paal
Outline

1. Characteristics of CSP
2. Market und Cost Development
3. Benefits for a mix of PV und CSP
4. Process Heat
5. Advances Heat Transfer Fluids
   • Volumetric Air Receiver
   • New silicon oil heat transfer fluid
   • Molten salt in parabolic troughs
6. Conclusions
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6. Conclusions
What is CSP?

Conventional power plant
What is CSP?

Concentrating solarpower plant
Trough vs. Tower

Line Focus

Point Focus

© DLR
Trough vs. Tower

- Solar energy collected by reflection
- Solar energy collected by piping
Thermal Storage vs. Electric Storage

CSP with thermal storage and fossil back provides reliable dispatchable power at no additional cost.
CSP only suitable in areas with high direct normal radiation
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Global expansion of CSP in three phases

Cost for CSP and PV have dropped dramatically

- Installed CSP capacity is more than an order of magnitude smaller than PV capacity

[Graph showing the decrease in module price and energy sales prices for CSP and PV over time]
Solar Electricity cheaper than power from gas!
700 MW @ 5500 h CSP á 7,3 $cents/kWh
+ 800 MW @ 2300 h PV a 3 $Cents/kWh
= 5,95 $cents/kWh
= 5,07 €cents/kWh
for 24/7 electricity

More than 5000 full load hours
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## Chile Scenario Results – Expansion Model
### Scenario 1

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<th>Social acceptance</th>
<th>Energy demand</th>
<th>Technological change in BESS</th>
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<th>RE investment costs</th>
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<tr>
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<td>High</td>
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<td>USD 50 /MWh by 2025</td>
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### Installed Capacity

- **2029**

- **CSP**
- **PV**

- **Key Technologies**:
  - Pump
  - Battery
  - CSP_Solar
  - PV_Solar
  - Wind
  - Other
  - Hydro_NCRE
  - Hydro_ROR
  - Hydro_Dam
  - Diesel
  - LNG
  - Geothermal
  - Biomass
  - Coal
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**CSP LCOE USD 50 /MWh by 2025**

**Generation**

- **2029**
  - **PV**
  - **CSP**

- **[GWh]**

- **x 10000**

- **Years:** 2016 to 2050

- **Energy Sources:**
  - Battery
  - Pump
  - Diesel
  - Diesel
  - CSP_Solar
  - Wind
  - Hydro_ROR
  - Hydro_NCRE
  - Geothermal
  - Other
  - Biomass
  - LNG
  - Hydro_Dam
  - Coal
Chile Szenario results: Short Term Simulation

2035 summer week dispatch by technology
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Process Heat Demand in Mediterranean Countries

Total Process Heat Demand

280 TWh/a

after 20 % energy savings
Process Steam Demand by Industry Sectors

Total: 113 TWh/a (after 20% energy saving)
Challenges in Solar Process Heat

- Heat cannot be transported easily over long distances
  - Meteorological conditions at the site
  - Availability of suitable areas for collectors (ground, roof, facades)

- Solar field size (= investment cost) proportional to heat demand
  - Rational use of energy minimizes heat demand
  - Process optimization more cost effective than “free” solar energy

- Collector efficiency temperature dependent
  - Selection of suitable collector technology
  - Integration of solar heat at appropriate temperature

- Annual, daily and stochastic variations of radiation
  - Load management, heat storage or conventional back-up
  - Similar load and radiation profiles may increase solar share

- O&M effort for additional technology
  - Priority for O&M personnel: Efficient production
  - Fully automated solar operation
Example: Solar Process Heat, Saignelieger, Switzerland

- NEP Solar: Cheese factory in Saignelégier, Switzerland.
- 17x NEP Solar PolyTrough 180 collectors Commissioning Sept. 2012
- Hot water/antifreeze circuit, 130 °C
- 627m², 400kW nominal heat capacity
Example Process Heat, New York City

- Steinway and Sons
- Long Island City, New York, USA
- Operational 2010
- 501 m²

- Back-up by natural gas

- Heating and cooling, process steam

- Humidity control of piano „action“ department
Example: Solar Process Heat at RAM Pharma, Amman, Jordan

- Solar field: linear Fresnel collectors of Industrial Solar GmbH
- Supply of saturated steam at 6 bar gauge
- Start of operation: March 2015

Collector field and steam drum with piping to steam network
## Economic Example for Jordan

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil Steam Generation Cost in 2017</td>
<td>81.7 €/MWh\textsubscript{th}</td>
<td>Only running cost; boiler efficiency 80%; ex. Rate 0.75 JOD/€</td>
</tr>
<tr>
<td>Turn-Key Investment Cost</td>
<td>766 000 €</td>
<td>i.e. 435 €/m\textsuperscript{2} (Industrial Solar costs – 10% incentives)</td>
</tr>
<tr>
<td>Running Cost per year</td>
<td>12 000 €</td>
<td>+1% per year</td>
</tr>
<tr>
<td>Equity Ratio</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>Debt Ratio</td>
<td>80%</td>
<td></td>
</tr>
<tr>
<td>Debt term</td>
<td>10 years</td>
<td></td>
</tr>
<tr>
<td>Debt funding interest rate</td>
<td>4%</td>
<td></td>
</tr>
</tbody>
</table>

### Economic Key Results

<table>
<thead>
<tr>
<th>Economic Key Results</th>
<th>Base Case</th>
<th>6% Interest</th>
<th>100% Equity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payback Time</td>
<td>2.3</td>
<td>2.7</td>
<td>4.8</td>
</tr>
<tr>
<td>Internal Rate of Return (IRR)</td>
<td>52</td>
<td>47</td>
<td>23</td>
</tr>
<tr>
<td>Levelized Heat Cost</td>
<td>41.4</td>
<td>41.4</td>
<td>41.4</td>
</tr>
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Energy from the sun: Open volumetric solar receiver

HiTRec-II
SiSiC honeycomb

Volumetric effect
What is the perfect absorber?

Honeycomb

Wire mesh

Foam
Different Characteristics affecting Flow Stability

- viscosity increases with increasing temperature
- hot zones are badly cooled
- local hot spots
- → instable flow at
  - high temperatures
  - linear pressure drop characteristics
  - low thermal conductivity
How can instable flow be visualized?

by thermograph monitoring of the cooling of a heated porous monolith
cordierite honeycomb

SiC foam

v = const.

v = 0 in hot channels

geometry/pressure loss characteristics influences flow stability

heat conductivity influences flow stability
Optimizing the Absorber Design

State-of-the-art

Increase cellularity and porosity

Unit element

Decrease inlet radiative losses

Unit element

Por.: 0.51 - 80 CPSI

Por.: 0.64 - 200 CPSI

Por.: var. - 200 CPSI
Optimizing the Absorber Design
Numerical Simulation

Innovative geometry
Optimized design

HiTRec-II

State of the art design

Temperature [K]

Sample depth

$T_{\text{air-out}}$: 1149 K
$\eta = 90\%$

$T_{\text{air-out}}$: 1012 K
$\eta = 72\%$
Prototype sample production by 3D printing

Cylindrical prototype test-sample: Ti6Al4V 3:1 scaled up geometry
Experimental Validation of Prototype

Thermal efficiency evaluation ‡ 20 kW solar simulator
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4. **Scientific Challenges in CSP Development**
   - Shape Accuracy of Solar Concentrators
   - **New silicon oil heat transfer medium**
   - Molten salt in parabolic troughs

5. Conclusions
Advanced Silicon Oil in Parabolic Troughs

- **Environmental Safety**
- **Capacity / Performance**
  - low pour point (-55°C) reduces auxiliary consumption for freeze protection
  - slower degradation at 425°C in comparison to DPO/BP at only 400°C
  - 425°C field outlet temperature increases conversion efficiency of Rankine cycle and allows for smaller heat storage systems
Advanced Silicon Oil in Parabolic Troughs

Enhanced thermal stability

- Comparison of DPO/BP at only 400°C with HELISOL® 5A at 425°C
  - Considerably slower formation of low boiling degradation products
  - Less hydrogen formation (enhanced receiver lifetimes expected)
Advanced Silicon Oil in Parabolic Troughs

<table>
<thead>
<tr>
<th>Heat transfer fluid</th>
<th>Unit</th>
<th>DPO/BP</th>
<th>HELISOL® 5A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal solar field temperature</td>
<td>°C</td>
<td>393</td>
<td>430</td>
</tr>
<tr>
<td>Gross power block efficiency (wet cooling)</td>
<td>%</td>
<td>39.0</td>
<td>40.5</td>
</tr>
<tr>
<td>Gross power block efficiency (ACC)</td>
<td>%</td>
<td>37.7</td>
<td>39.2</td>
</tr>
<tr>
<td>Nominal specific solar field parasitics</td>
<td>W/m²</td>
<td>8</td>
<td>6.4</td>
</tr>
<tr>
<td>Specific investment solar field</td>
<td>€/m²</td>
<td>235</td>
<td>235</td>
</tr>
<tr>
<td>Specific investment storage</td>
<td>€/kWh</td>
<td>40</td>
<td>33</td>
</tr>
<tr>
<td>Specific HTF cost (identical)</td>
<td>€/kg</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Annual HTF replacement rate (identical)</td>
<td>%</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Mean volumetric heat capacity</td>
<td>kJ/(m³K)</td>
<td>1871</td>
<td>1397</td>
</tr>
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</table>

Benefits over DPO/BP state-of-the-art thermal oil
- Increased performance due to higher live steam temperatures
- Lower storage costs due to increased temperature spread
- LCOE by cost reduction potential of about 5% for different sites and plant sizes
German-Spanish cooperation

PROMETEO test facility at Plataforma Solar de Almería (Spain)
- Durability and loop scale applicability of HELISOL® 5A at 425°C
- Comprehensive laboratory analysis – degradation
- Functionality parabolic trough collector components at up to 450°C
  - Receiver Tubes
  - Rotation and expansion performing assemblies
- Economic benefit of HELISOL® 5A
  - technical investments / greater energy output
  - Safety concept and (permitting process for relevant target markets)
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Molten Salt in Parabolic Trough Power Plants

Advantages of the Molten Salt System

- Higher overall system efficiencies due to higher working parameters (up to 565°C/150 bar instead of 400°C/100 bar)
- Solar Field and power block fully decoupled
- Lower price for heat transfer fluid (HTF), no need of heat exchangers and additional pumps
- Environmentally friendly heat transfer fluid vs. thermal oil
Parabolic Trough Night operation /w molten salt

- Minimum temperature in solar field must not drop to solidification temperature of the salt

- Choice of salt defines hours of so called anti-freeze operation of a cooled down solar field, e.g. during night and overcast times

- Energy for anti-freeze operation during night and overcast situations is provided by the sun! Part of the thermal energy storage is reserved for anti-freeze and loaded during the day. Only in seldom cases of exception a fossil burner supports.

<table>
<thead>
<tr>
<th>Salt Mixtures</th>
<th>Decomp. Temperature</th>
<th>Freezing Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS-A NaK-NO₃ (Solar Salt)</td>
<td>&gt;550°C</td>
<td>238°C @ 60/40 Mixture</td>
</tr>
<tr>
<td>MS-B NaKCa-NO₃</td>
<td>&lt;500°C</td>
<td>~150°C</td>
</tr>
<tr>
<td>MS-C NaKLi-NO₃</td>
<td>~530°C</td>
<td>~140°C</td>
</tr>
</tbody>
</table>
Proof of concept needs to show:

1. Filling and draining of the plant
2. Anti-freeze parasitic load
3. Danger of freezing
4. Blackout scenarios
5. Corrosion at high temperature
6. System performance
7. Flexible connection technology: Proof of functionality and tightness
8. Steam Generating System leakage
9. Maintenance procedures
10. Stability of salt mixtures
DLR’s objective in Évora, Portugal: to confute all concerns

Project: HPS2 – High Performance Solar 2
Commissioning of the plant: May 2018

See also: http://www.dlr.de/sf/en/desktopdefault.aspx/tabid-10436/20
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Conclusion

- CSP troughs and towers with large thermal energy storage systems are commercial products today

- In combination with PV, CSP is competitive to 24/7 power from natural gas under favorable conditions

- For solar collectors can replace fuel oil when integrated into a process heat steam supply at grid achieving pay-back periods of < 4 years

- With 5 GW installed the technology is very young and significant further improvement is feasible

- Major future challenges are related to integrate new power cycles that operate at elevated temperatures and require new heat transfer and storage fluids