Thermal Energy Storage for Concentrated Solar Power: State of the Art and Current Developments

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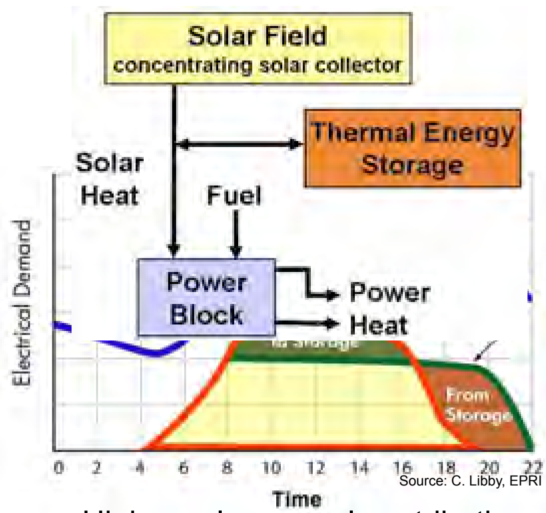
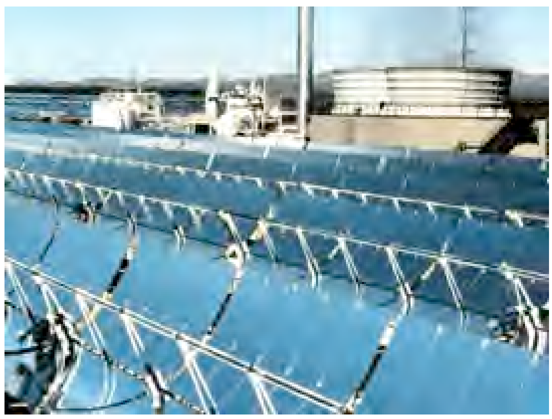
ISES Annual Meeting

Tel Aviv University, October 5, 2011

Energy Storage for Concentrating Solar Power Plants





- Higher solar annual contribution
- Reduction of part-load operation
- Power management
- Dispatchable power

Energy storage necessary for successful market implementation of CSP technology

Thermal Energy Storage
Challenges

Highly specific design specifications regarding:
primary HTF - pressure - temperature - power level - capacity

synthetic oil	trough	15 bar	400 °C
saturated steam	tower	40 bar	260 °C
superheated steam	trough	50-100 bar	400-500 °C
molten salt	tower/ trough	1 bar	500-600 °C
air	tower	1 bar	700-1000 °C
air	tower	15 bar	800-900 °C
	new concepts		

⇔ Storage system ⇔

ORC
steam turbine
gas turbine
combined cycle
Stirling engine
others

ONE single storage technology will not meet
the unique requirements of different solar power plants

Storage concepts for parabolic trough power plants
Classification

Heat transfer fluid as storage media

Direct active thermal energy storage → **Two tank storage (oil/molten salt)**; **Steam Accumulator**

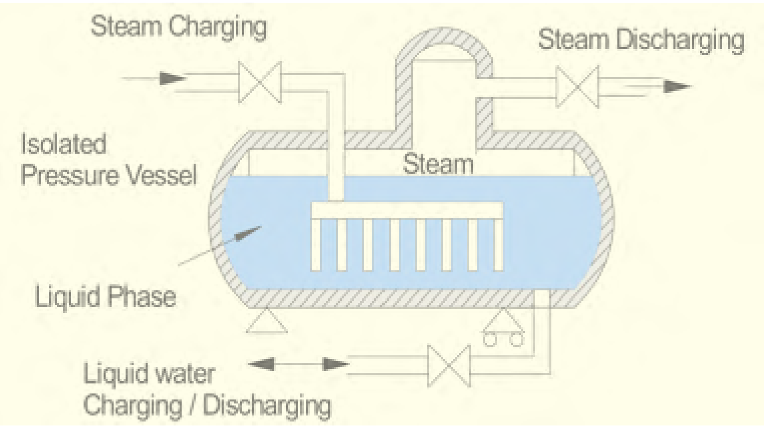
Dual medium storage system

Passive thermal energy storage →
- liquid → **Molten salt sensible heat storage**
- solid → **Solid media sensible heat storage**
- phase change → **Latent heat storage**

Thermal Energy Storage for CSP Plants
Status und Development

- **Commercially available storage systems**
  - Steam Accumulator
  - 2-Tank sensible molten salt storage based on nitrate salts
- **Alternative materials and concepts tested in lab and pilot scale**
  - Improved molten salt storage concepts
  - Solid medium sensible heat storage, e.g. concrete storage
  - Latent heat - PCM storage
  - Combined storage system (concrete/PCM) for water/steam fluid
  - Solid media storage for Solar Tower with Air Receiver (e.g. natural rocks, checker bricks, sand)
  - Thermo-chemical storage
- **Future focus for CSP**
  - Higher plant efficiency => Increase process temperature
  - New fluids: steam, molten salt, gas/air

State-of-the-Art - Steam Accumulators
Storage of sensible heat in pressurized liquid water



Charging process:
raising temperature in liquid water volume by condensing steam

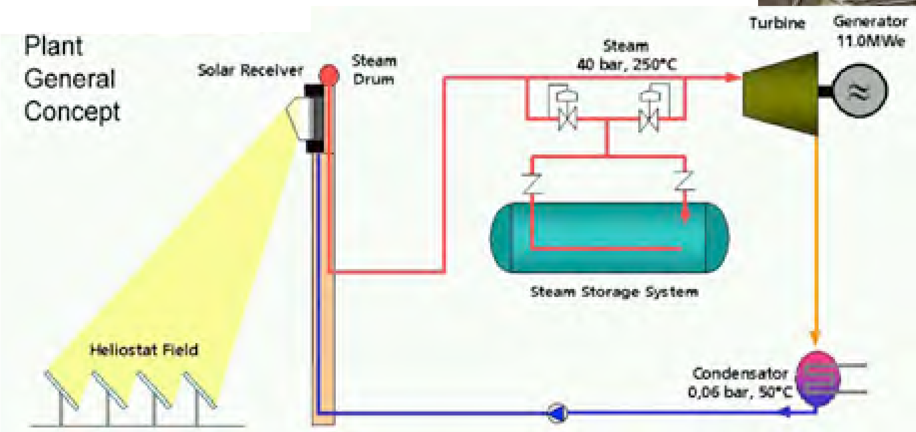
Discharging process:
generation of steam by lowering pressure in saturated liquid water volume

→ Buffer storage for peak power

→ Inefficient and economically not attractive for high pressures and capacities

State-of-the-Art - Steam Accumulators
PS10

Saturated steam at 250°C
50 min storage operation at 50% load

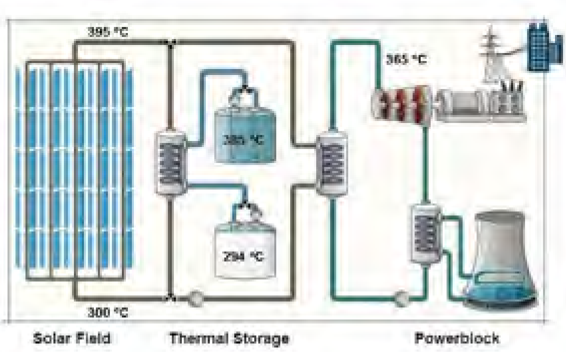


State-of-the-Art - Steam Accumulators
PS10

State-of-the-art - Molten salt storage
Indirect 2-Tank Storage

Andasol

- Storage capacity 1010 MWh (7.7h)
- Nitrate salts
  (60% NaNO3 + 40% KNO3)

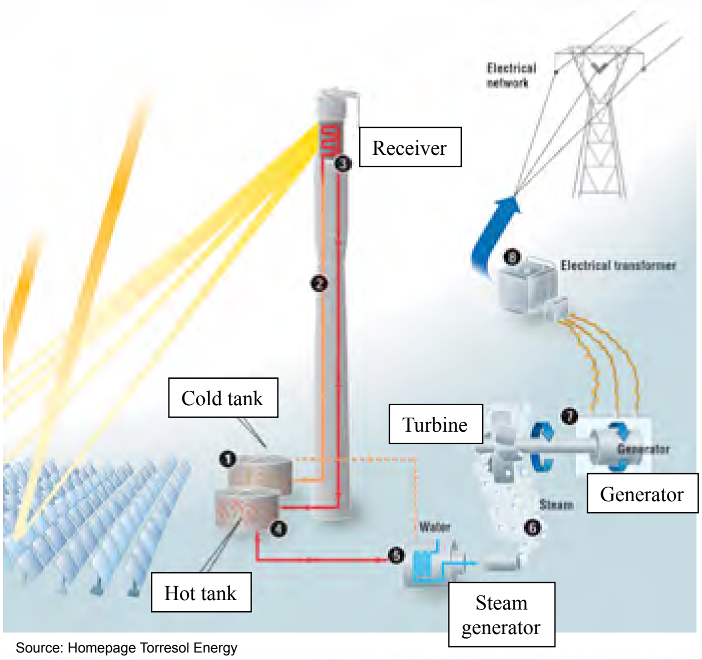


- Salt inventory 28.500 t
- Tank volume 14.000 m³
- 6 HTF/salt heat exchangers

Source: Kolb, G. J., 2010, Evaluation of Annual Performance of 2-Tank and Thermocline Thermal Storage System for Trough Plants, Solar Paces 2010, Perpignan, France.
Relloso, S., Delgado, E., 2009. Experience with Molten Salt Thermal Storage in a Commercial Parabolic Trough Plant, Solar Paces 2009, Berlin, Germany.

State-of-the-art - Molten salt storage
Direct 2-Tank Storage

- Heat transfer fluid and storage medium are the same
- 1st system: Solar Two Project by Sandia
- 2nd commercial system at Gemasolar plant: *Solar Tower plant with 15 h storage*



Source: Homepage Torresol Energy

STORAGE IN TOWER PLANTS. ADVANTAGES & GMSP EXPERIENCE

- TOWER WITH STORAGE. THE SAME FLUID IS USED AS THE HEAT TRANSFER AND STORAGE MEDIUM.
- HIGH STORAGE CAPACITY. ENERGY AVAILABLE AND DISPATCHABLE ON DEMAND. SOLAR ENERGY COVERS PEAK DEMANDS, DAY AND NIGHT. 24 H PRODUCTION CONTINUOUSLY FROM SOLAR ENERGY STORED
- HIGHEST STEAM TEMPERATURE (540ºC). HIGHEST THERMODYNAMIC CYCLE EFFICIENCY
- MOLTEN SALT SYSTEM (PIPING & STORAGE TANKS) IS CONCENTRATED IN A SMALL AREA (RADIUS = 20 M). THERMAL LOSS, PRESSURE DROP, LEAKS, MAINTENANCE COSTS MINIMIZED.
- GMSP: 15 HOURS STORAGE AT 19 MW (MORE CAPACITY THAN PT FOR THE SAME MASS: ~3 TIMES)
- GMSP. FIRST COMMERCIAL MOLTEN SALT TOWER FACILITY IN THE WORLD . PROVEN TECHNOLOGY WITH VERY HIGH PLANT AVAILABILITY
- MOLTEN SALTS TOWER PLANTS HAVE MANY ADVANTAGES AND LESS ENERGY COST, IN COMPARISON TO PT PLANT OF THE SAME ST RATED POWER. TOWER PLANT WITH STORAGE MEANS THE CSP FUTURE PLANTS TECHNOLOGY

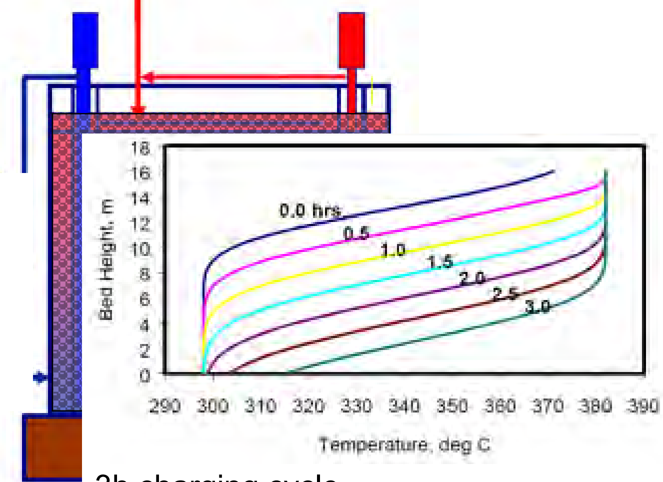
Current Developments - Thermocline

HTF from Field

+ Cost reduction potential: approx. 33 %

- No long term experience have been published so far

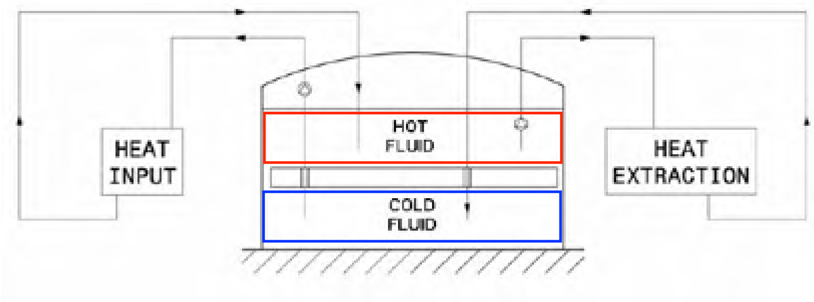
HTF Return



3h charging cycle

Thermocline Tank

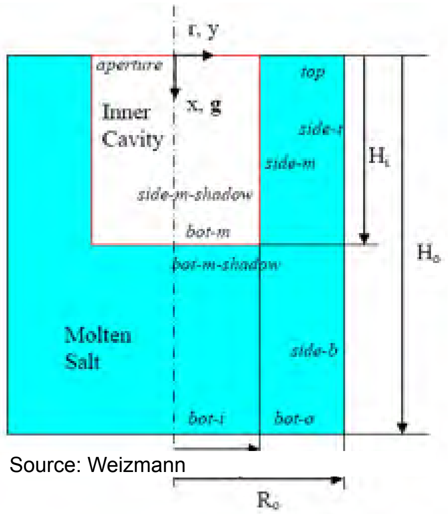
Current Developments - Thermocline
Floating Barrier



+ Only one tank necessary

- Nearly the same amount of salt as in 2-Tank storage

Current Developments - Thermocline
Embedded heat exchanger / receiver



Source: Weizmann

Source: Fabrizi, F., 2007, ENEA

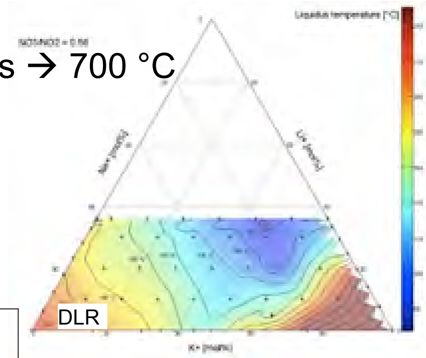
Current Developments – New Salt Mixtures

Demand for…

…higher thermal stabilities of molten salts → 700 °C

…Lower melting points → < 140 °C

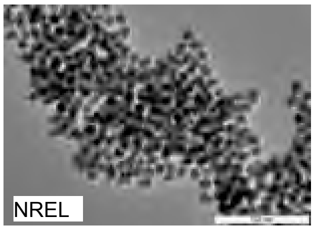
…improved thermo-physical properties



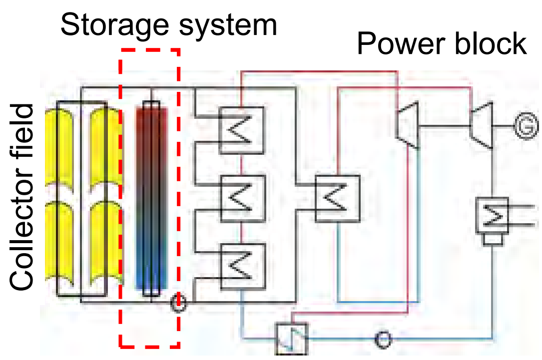
- Research on new salt mixtures:

Ternary system	$Ca(NO_3)_2$-KNO_3-$NaNO_3$
Quaternary system	Li, Na, K // NO_2,NO_3

- Heat capacity enhancement by nano particles



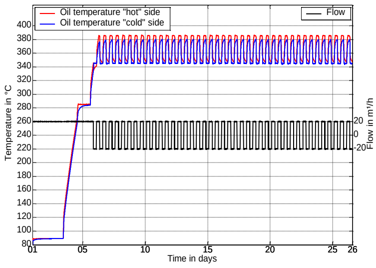
Alternative Storage Technology for Trough Plants with Oil HTF – Concrete Storage



- Heat transfer fluid and storage medium are different
- Low cost storage material with integrated heat exchanger
- No risk of solidification
- Modular and scalable design
- Economic and reliable TES (< 35 € / kWh TES capacity)
- Flexible to large no. of sites and construction materials

Status of Concrete Storage

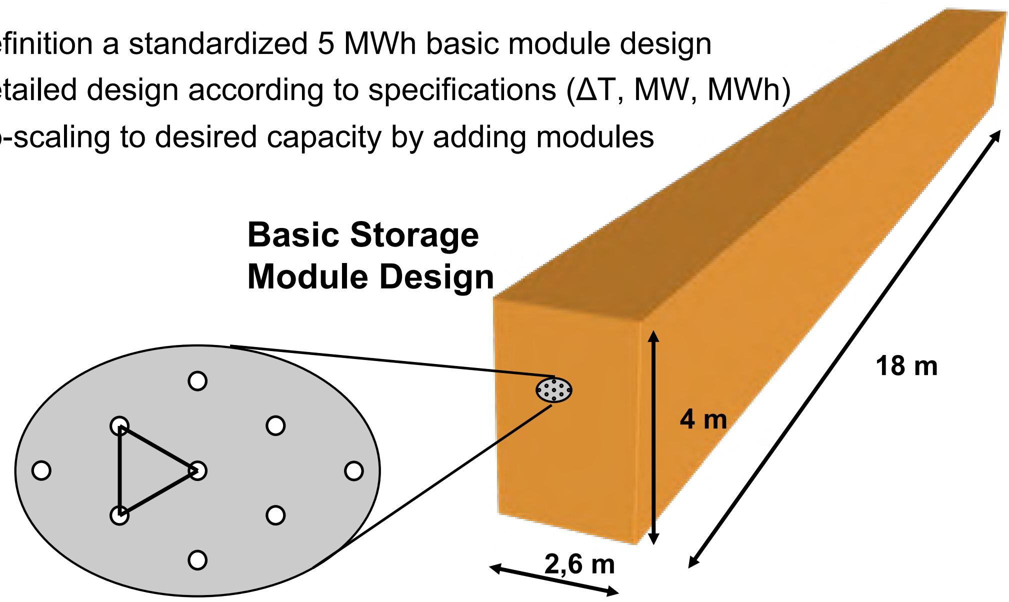
- 400 kWh pilot storage in operation since May 2008
- Storage capacity: 0.65 kWh/ (m^3·K)
- Over 10,000 operation hours
- No indication of any degradation effects



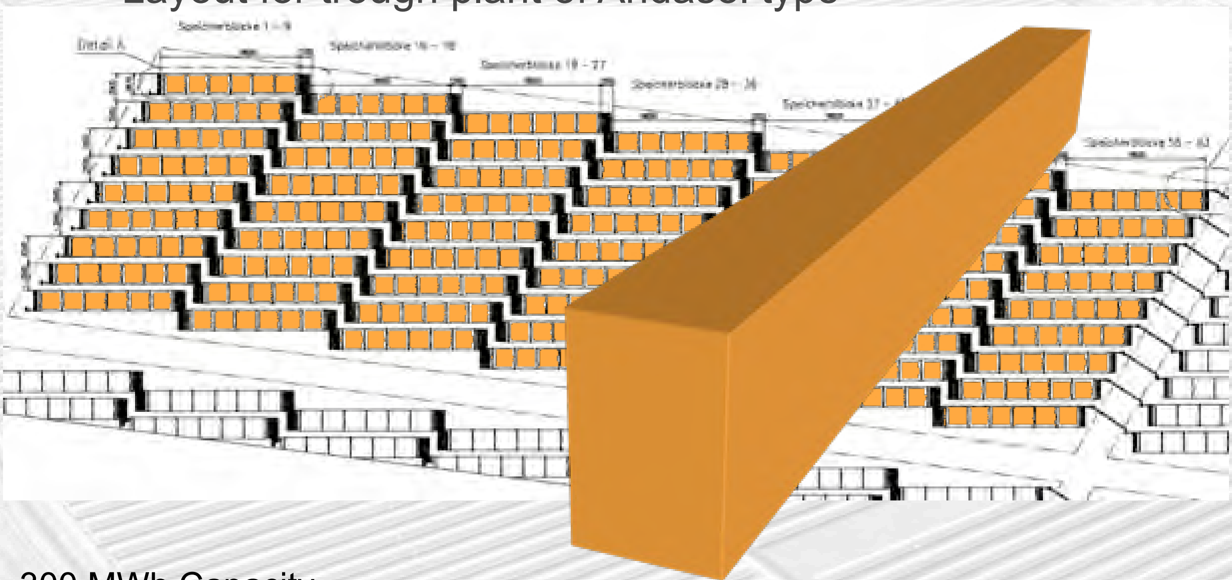
2nd Generation Pilot Storage built 2008

Concrete Storage
Strategy for commercialization

- Definition a standardized 5 MWh basic module design
- Detailed design according to specifications (ΔT, MW, MWh)
- Up-scaling to desired capacity by adding modules

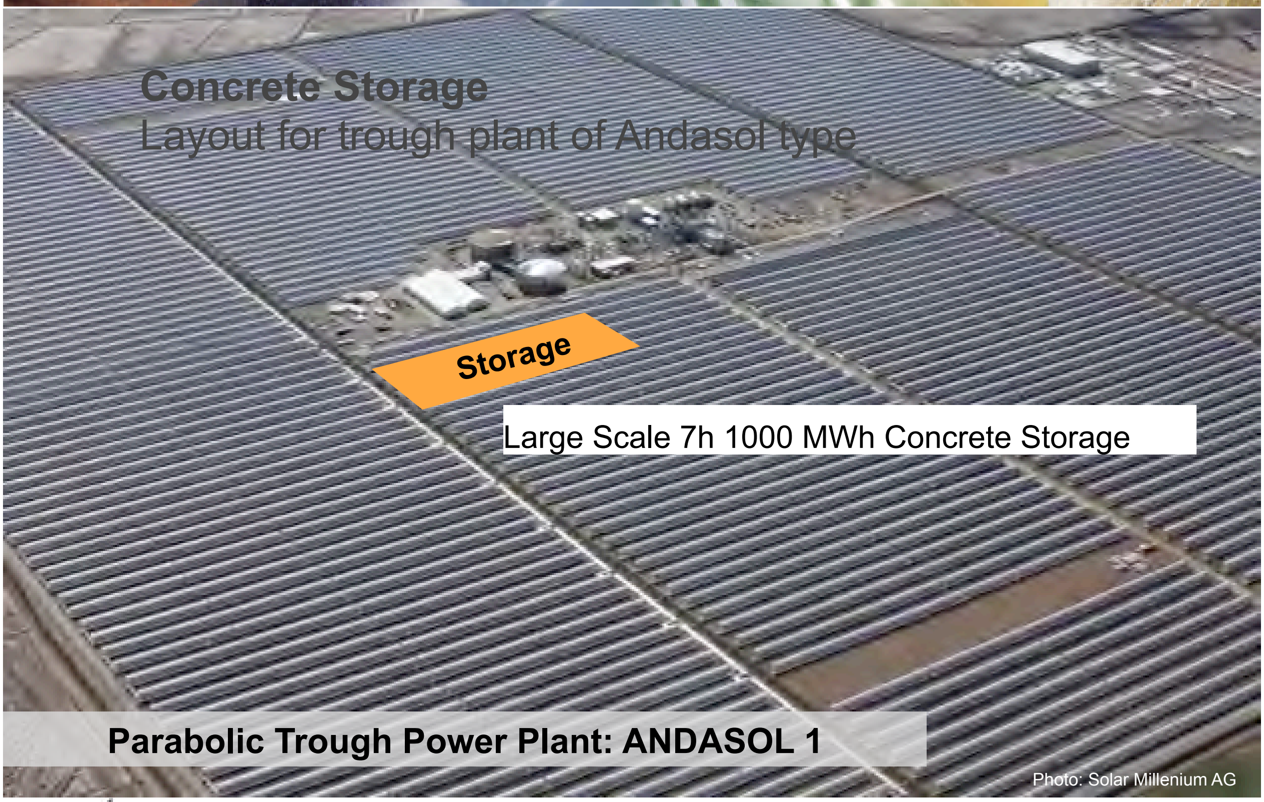


Concrete Storage
Layout for trough plant of Andasol type



300 MWh Capacity
Configuration of 7 x 9 = 63 modules

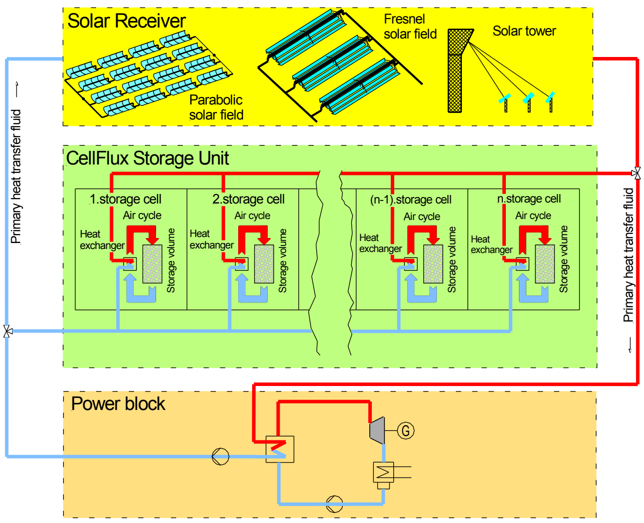
Concrete Storage
Layout for trough plant of Andasol type



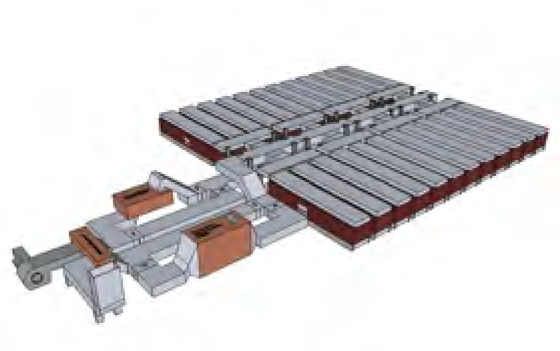
Parabolic Trough Power Plant: ANDASOL 1

Photo: Solar Millenium AG

Solid Media Storage Technology
New concepts - Air as intermediate heat transfer fluid



DLR



enolcon GmbH

Solid Media Storage Technology
New concepts – Air as intermediate heat transfer fluid

Problems with air

- Low volume specific energy density of air
  - Large pressure losses
  - Part load operation difficult

Challenge

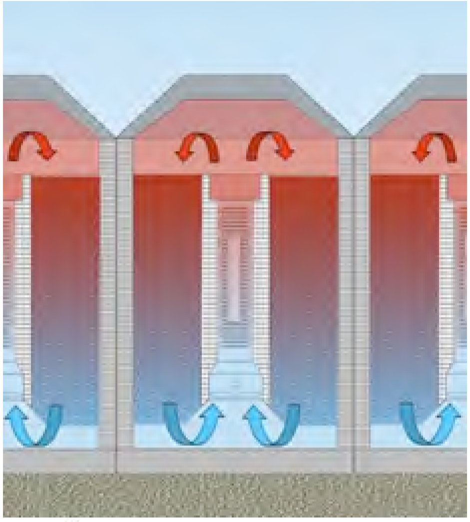
- Minimization of power needed for circulation of air
- Minimization of overall temperature differences
- Minimiziation of costs

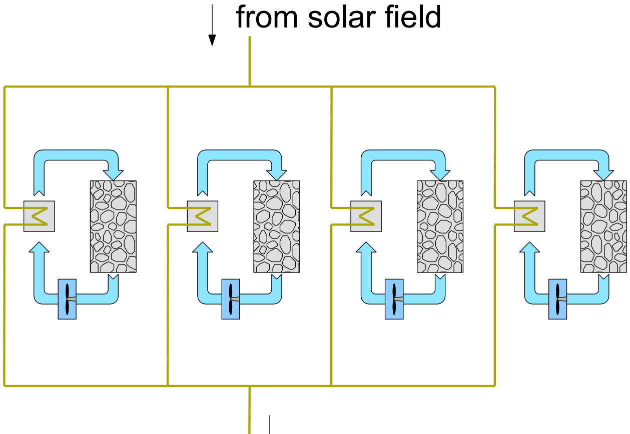
Solution

- Many parallel air cycles

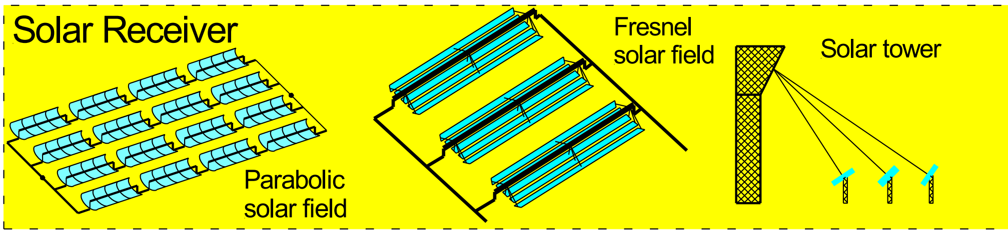
Solid Media Storage Technology
New concepts – Air as intermediate heat transfer fluid

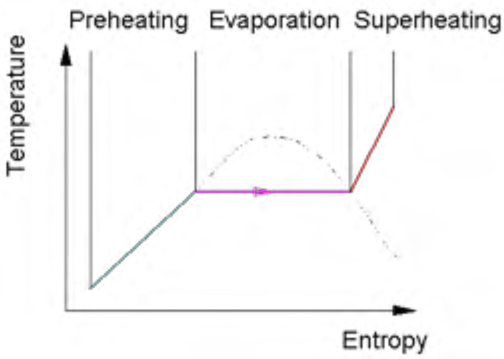
- Many parallel air cycles:

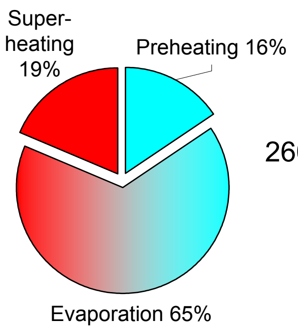




Storage Systems for DSG Plants
Latent Heat Storage





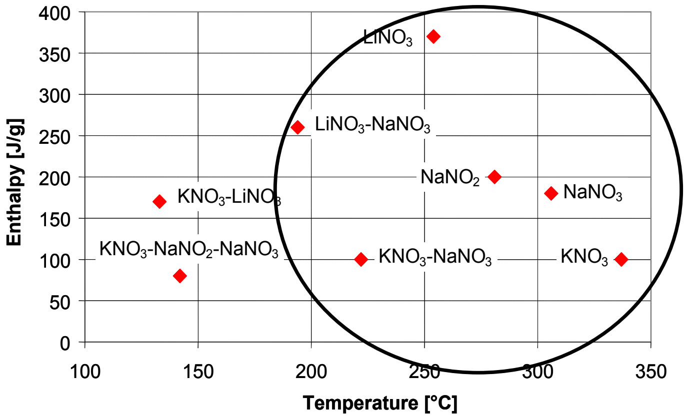


260 °C – 400 °C
107 bar

Latent Heat Storage

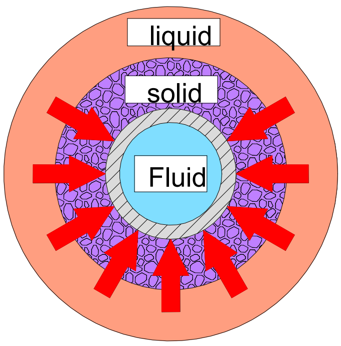
Features of PCM (phase change material) Storage

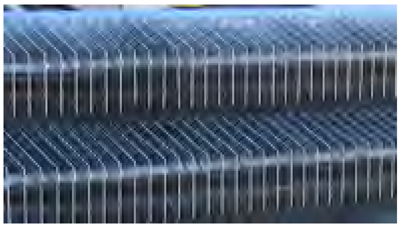
- Nitrate salt represent possible PCMs for applications beyond 100 °C
- Important PCM criteria: thermal conductivity, heat capacity, thermal stability, material cost, corrosion, hygroscopy



Latent Heat Storage

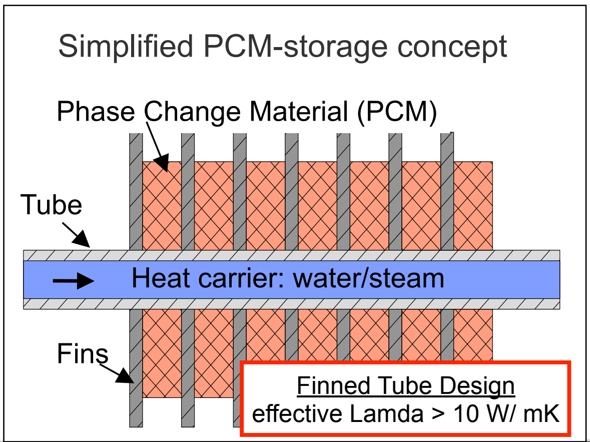
Enhancement of heat transfer





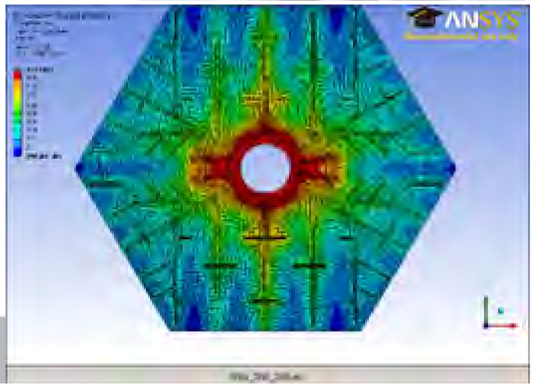
Heat transfer coefficient is dominated by the thermal conductivity of the solid PCM

→ Low thermal conductivity is bottleneck for PCM



Latent Heat Storage
Enhancement of heat transfer

Extruded longitudinal Fins:
- Cost-effective production and assembly
- Free flow path in vertical direction => no risk with volume change during phase change
- Controlled distribution of heat in the storage
- Concept optimized by FEM analysis
- Successful demonstration in lab-scale
- Major cost reduction expected



Status of Latent Heat Storage

Phase change material
Demonstrated at DLR:

$NaNO_3$ - KNO_3 - $NaNO_2$	142 °C
$LiNO_3$ - $NaNO_3$	194 °C
$NaNO_3$ - KNO_3	222 °C
$NaNO_3$	306 °C

Storage concepts

Graphite fins / horizontal tubes	< 250 °C
Aluminum fins / vertical tubes	< 350 °

Experimental validation
- 5 test modules with 140 – 2000 kg PCM
- Worlds largest high temperature latent heat storage with 14 tons of $NaNO_3$ (700 kWh) operating since 2010

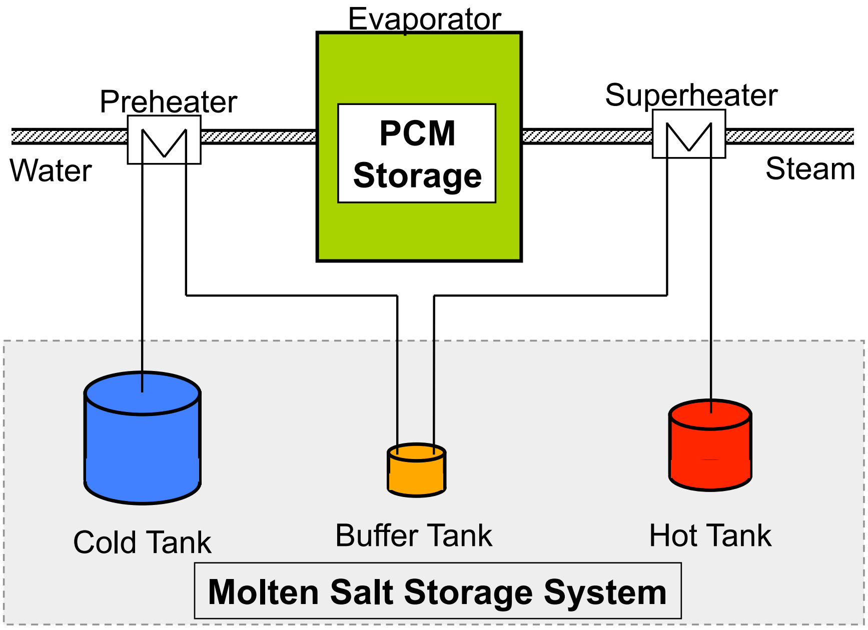
Combined Storage System for DSG
1 MWh Concrete Superheater and PCM-Storage

PCM-Evaporator module:
- PCM: $NaNO_3$
- Melting point: 306 °C
- Salt volume: 8.4 m³
- Total height 7.5 m
- Inventory ~ 14 t
- Capacity ~ 700 kWh

Concrete Superheater module:
- Concrete: 22 m³
- 144 tubes
- Length 13.6 m
- Capacity ~ 300 kWh

Test facility at Endesa ‘s Power Plant Litoral Carboneras, Spain

Combined Storage System
for direct steam generation in parabolic troughs

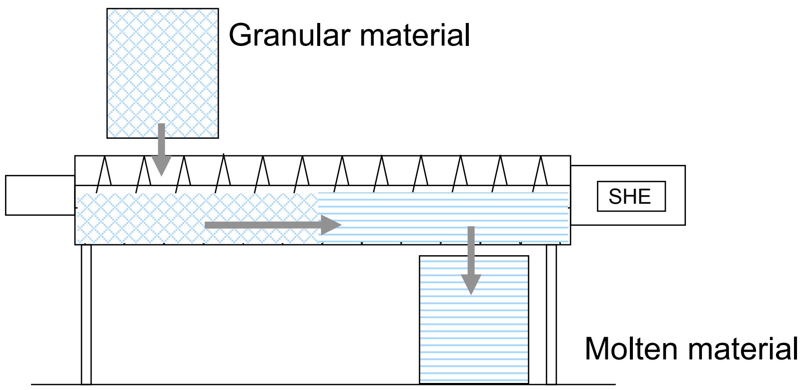


Latent Heat Storage (INNOLAT-CSP)
Latent Heat Storage with external HX - Principle

Fraunhofer ISE

Separation of thermal power and storage capacity in latent heat storage

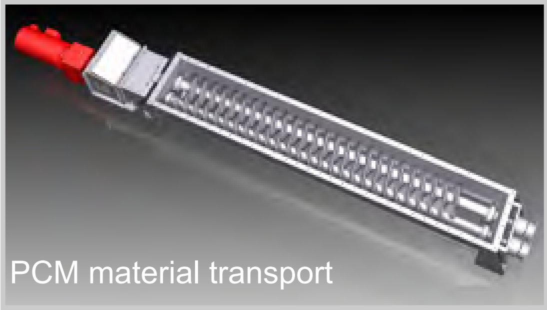
- Solid granular salt and molten salt are stored in separate tanks
- Transport of PCM through screw heat exchanger (SHE)
- Phase change inside SHE

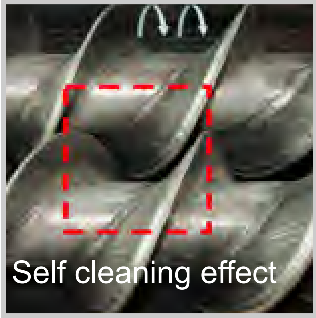


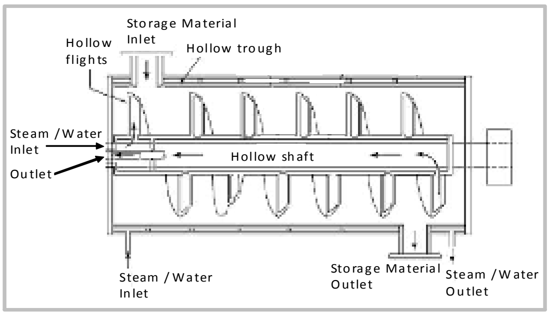
Latent Heat Storage (INNOLAT-CSP)

Screw heat exchanger (SHE)

Fraunhofer ISE



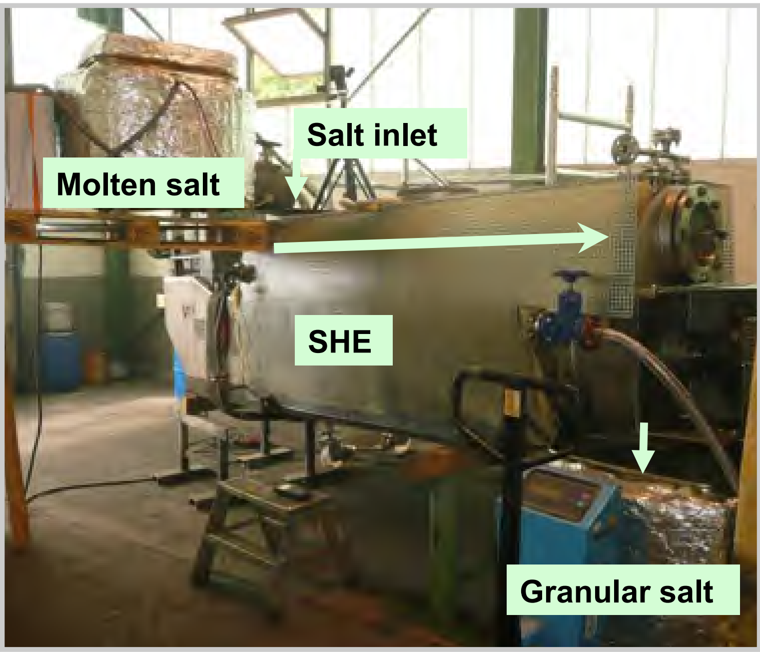




Latent Heat Storage (INNOLAT-CSP)

Proof of concept: Experimental Set-Up

Fraunhofer ISE



- **Proof of concept** already yielded Qth = 10 kW

Outlook

- Process and material optimisation
- Two prototype setups to be installed at Fraunhofer ISE labs:
  - 1st Prototype using thermal oil as HTF
  - 2nd prototype using steam as HTF
- Concept for upscaling

Latent Heat Storage (INNOLAT-CSP)
Proof of concept: Details

Fraunhofer ISE


Molten salt inlet


Cristallization of salt


Obtained salt granules


Piece of salt

Active HX with Freezing Salt Slurry PCM Thermal Storage

terrafore

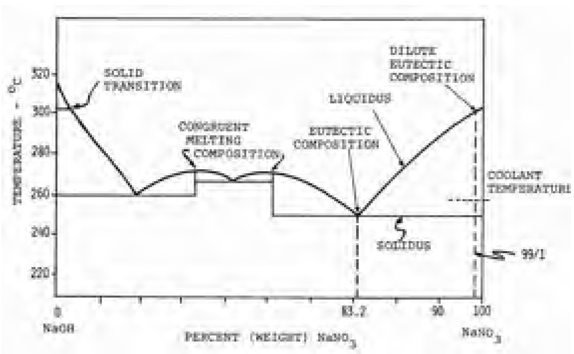
Courtesy: A. Mathur

Technology Challenge

- Continuously remove freezing salt from heat exchanger tubes to improve heat transfer coefficient and pump salt slurry

Terrafore Solution

- A *dilute eutectic* composition of salt mixtures that form a eutectic with a specific phase diagram called *simple* phase diagram
- A coating on the heat exchanger tubes that discourages strong adhesion of freezing salt



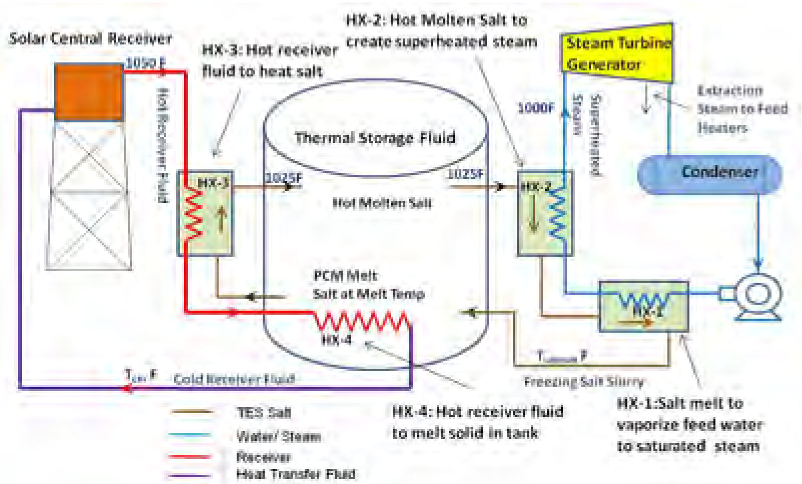
Active HX with Freezing Salt Slurry PCM Thermal Storage

terrafore

Courtesy: A. Mathur

Benefit

- A single tank can reduce amount of salt by over 25% and container by 60% over two tank TES.



Encapsulated PCM Thermal Energy Storage

terrafore

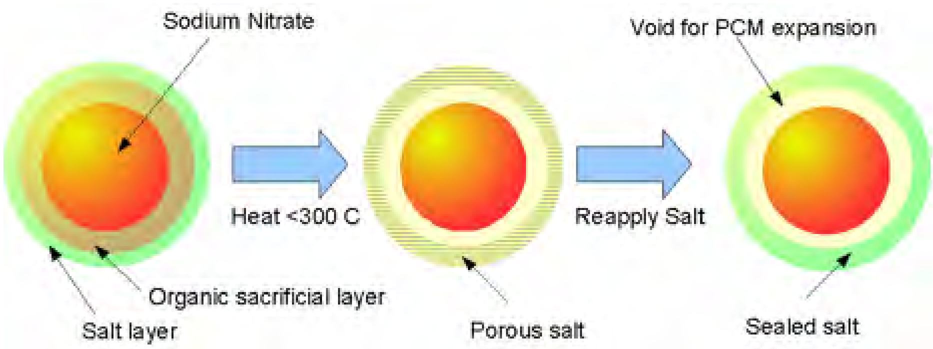
Courtesy: A. Mathur

Technology Challenge

- Create a void inside the capsule for expansion of salt during manufacture of capsules using contract manufacturing methods

Terrafore Solution

- Use a sacrificial polymer during the encapsulation process



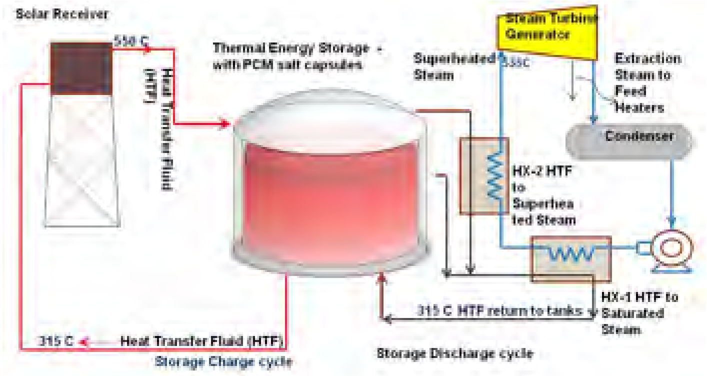
Encapsulated PCM Thermal Energy Storage

terrafore

Courtesy: A. Mathur

Benefit

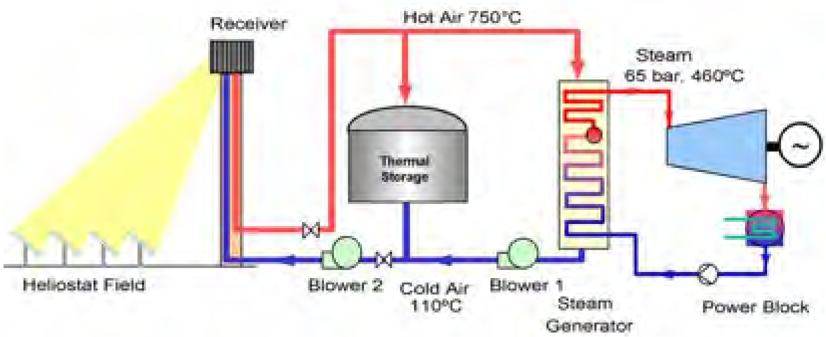
- A single tank with micro-capsules of salt mixtures melting at progressively higher temperatures can reduce amount of salt by over 20% and container by 50% over two tank TES



A Thermal Energy Storage System Configuration

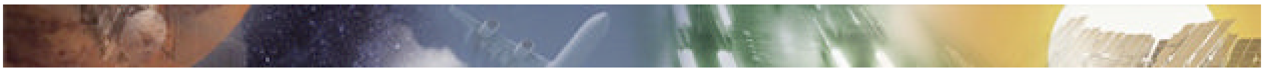
Storage for Solar Tower Plants with Air Receiver

Regenerator Storage



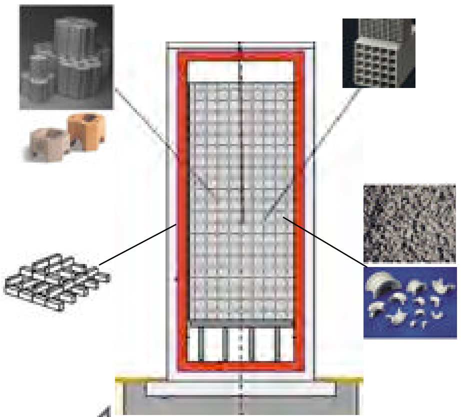
Source: Kraftanlagen München

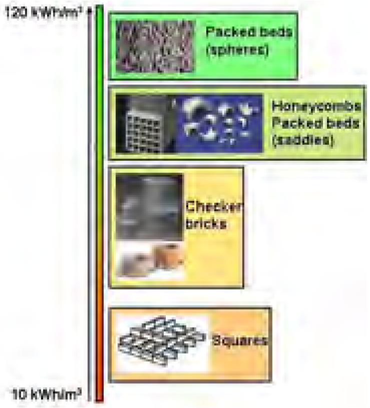
- Regenerator storage is a suitable heat storage technology for air receiver technology
  - Simple setup, allows use of low-cost storage materials
  - Direct contact air / storage material
  - Can be used up to very high temperatures
- 9 MWh demo storage at 1.5 MWe experimental Solar Tower Plant in Jülich, Germany

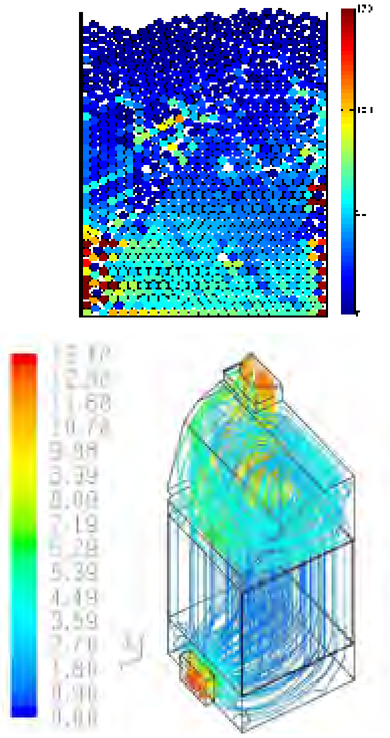


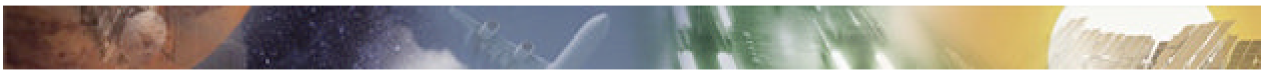
Storage for Solar Tower Plants with Air Receiver
Regenerator Storage - Challenges

- Durability of inexpensive storage materials
- Containment technology and HT-insulation
- Thermo-mechanical issues
- Even flow distribution through storage material

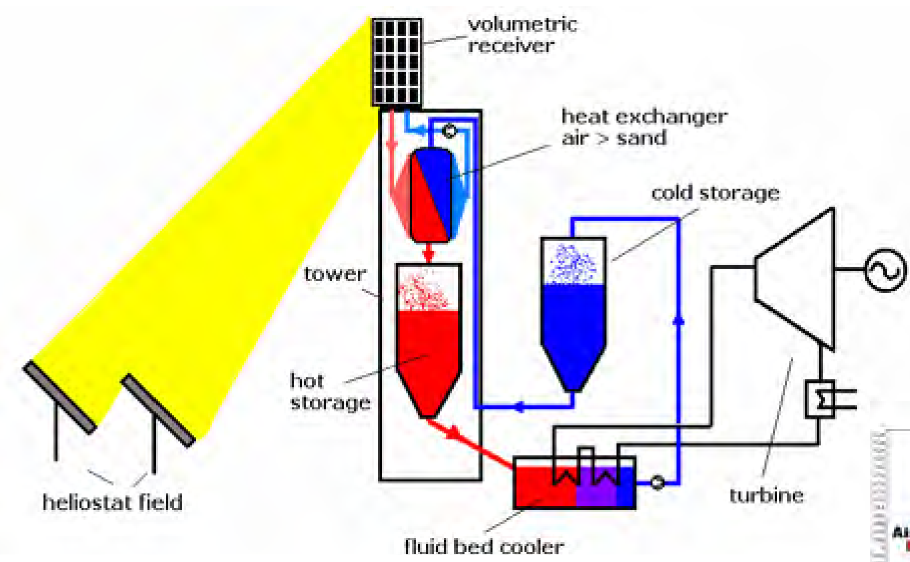




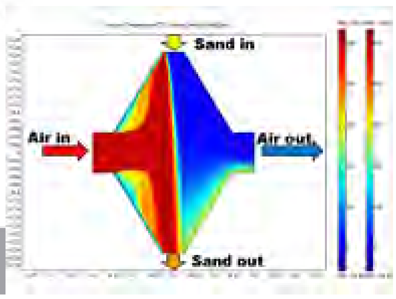




Solid Media Storage Technology
Sand storage - Air-sand heat exchanger

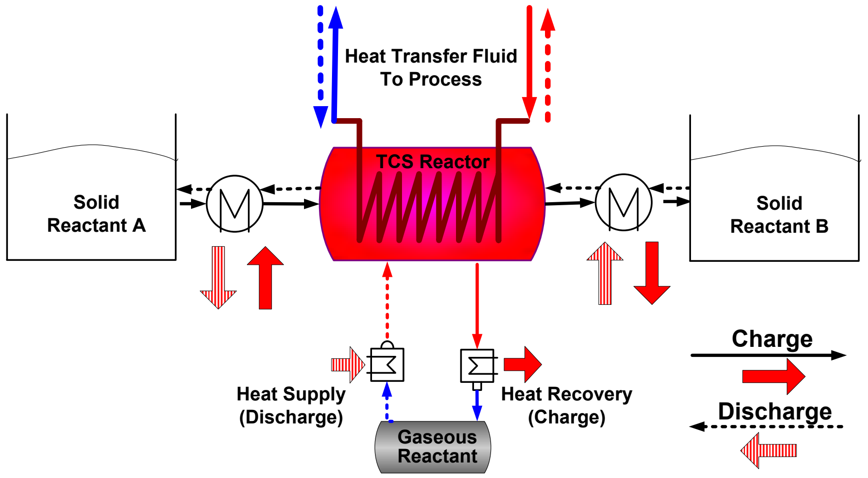


Solar Institute Jülich/DLR



Thermo-chemical Heat Storage
Reversible Gas-Solid Reactions

Solid Reactant A + ΔH ⇄ Solid Reactant B + Gas



Thermo-chemical Heat Storage
Potential and Challenges

Potential of TCS

- High storage density
- Application in a wide temperature range (50 to above 1000°C)
- Loss-free and long-term storage
- Heat transport and heat transformation possible

Challenges of TCS

Reaction System / Material

High reaction enthalpy
Thermodynamic euqilibrium

Cycling stability
Thermo-physical properties
Reaction kinetics

Reactor and Process Design

Type of reactor
Heat / mass transfer + reaction kinetics
Handling of solid reactants

Heat transfer to process (HTF)
Parasitics

Process Integration

Integration with CSP | Thermal/materials management | Mode of operation

Thermo-chemical Heat Storage
Closed Loop System $Ca(OH)_2 + \Delta H \leftrightarrow CaO + H_2O$

Rationale

- Well known process
- Low cost material, availability no problem
- Completely reversible
- No complicated side reactions and defined solid phases

Application for

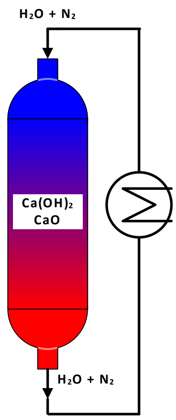
- Temperature range from 300 – 700°C

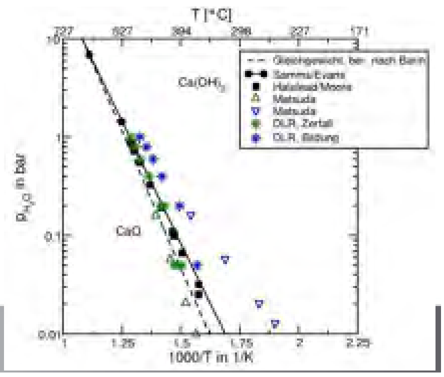
Theoretically achievable storage densities

T_{eq}[1 bar]	ΔH [1 bar]	Storage Density *		
		Solid only	Solid + Gas	Mass related
°C	*kJ/mol*	*kWh/m³*	*kWh/m³*	*kWh/t*
507	**100**	**410**	**323**	**373**

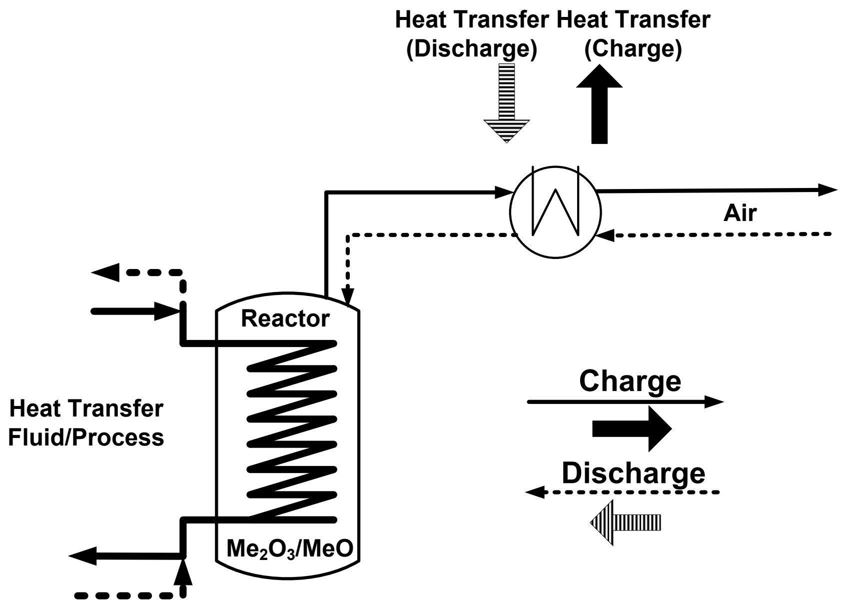
**Porosity of 0.5*

Thermo-chemical Heat Storage
Experimental Setup

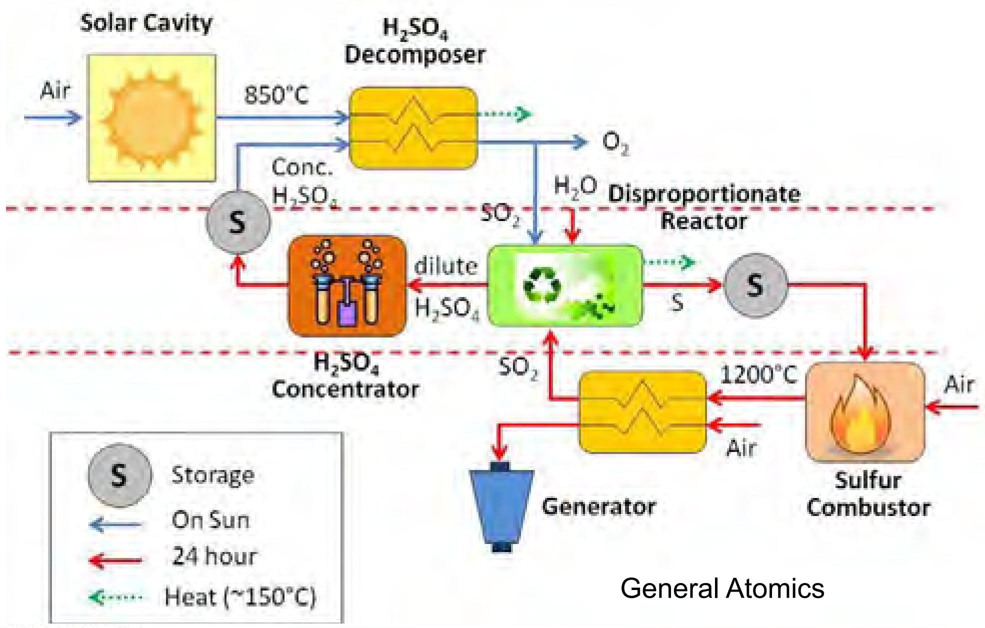




Thermo-chemical Heat Storage
Open loop metal-oxide based reactions with air



Thermo-chemical Heat Storage
Sulfur based thermo-chemical storage



General Atomics

Thermal Energy Storage for Concentrated Solar Power
Summary and Conclusions

- Energy storage is a key issue for CSP → dispatchability & efficiency
- Steam accumulators: Commercial, only economic as buffer storage
- Molten salt technology: Commercial concepts for indirect/direct 2-tank storages are available → Further research aims at cost reduction (new materials & concepts)
- Concrete storage technology is attractive alternative → demonstration in pilot scale needed
- PCM storage technology is the most promising technology for DSG plants → demonstrated in 1 MW scale
- Storage systems for air cooled receivers are currently being tested
- New storage solutions, e.g. TCS, are in a basic research stage
- Continuous research and development effort is needed especially for higher process temperatures (> 400°C) and for further cost reduction