Thermal Energy Storage for Concentrated Solarthermal Power Plants

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Sept. 13, 2013

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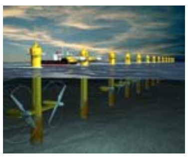
Why Concentrated Solarthermal Power Plants?

Renewable energies for power production


Run-of-the-river

Geo-thermal


Solarthermal power plants


Tides


Waves


Photovoltaic


Wind

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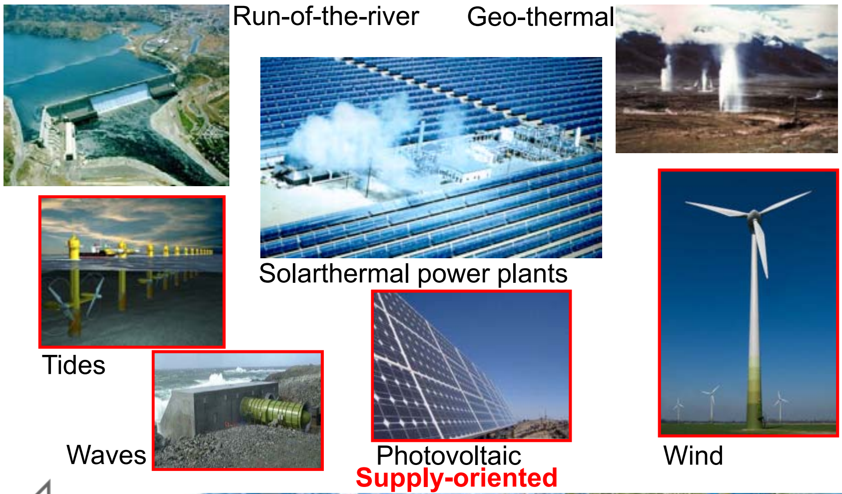
Integration in the electricity supply system
Adaptation to electricity demand



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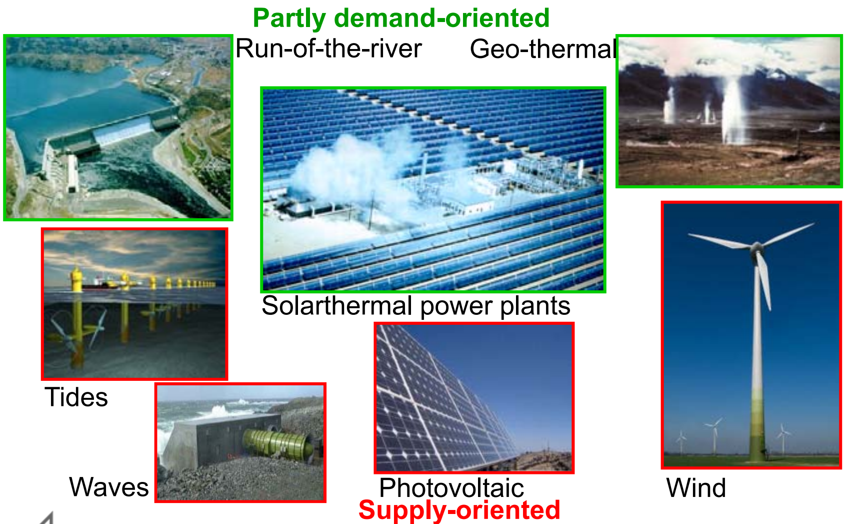
Integration in the energy supply system
Adaptation to electricity demand



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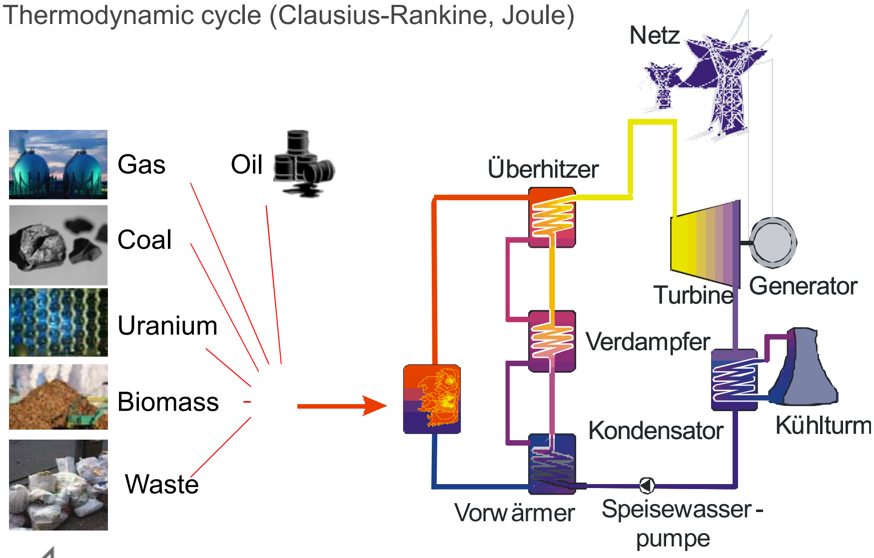
Principle of solarthermal power plants

Thermodynamic cycle (Clausius-Rankine, Joule)



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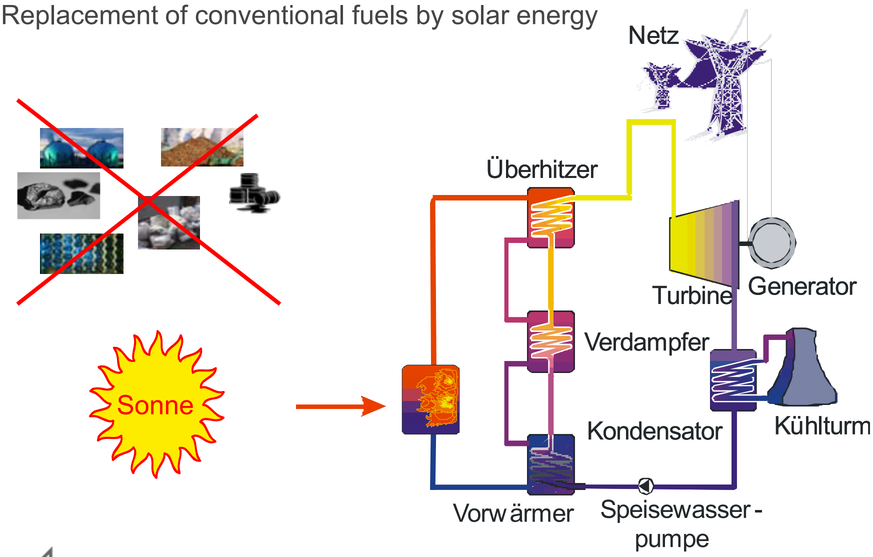
Principle of solarthermal power plants

Replacement of conventional fuels by solar energy



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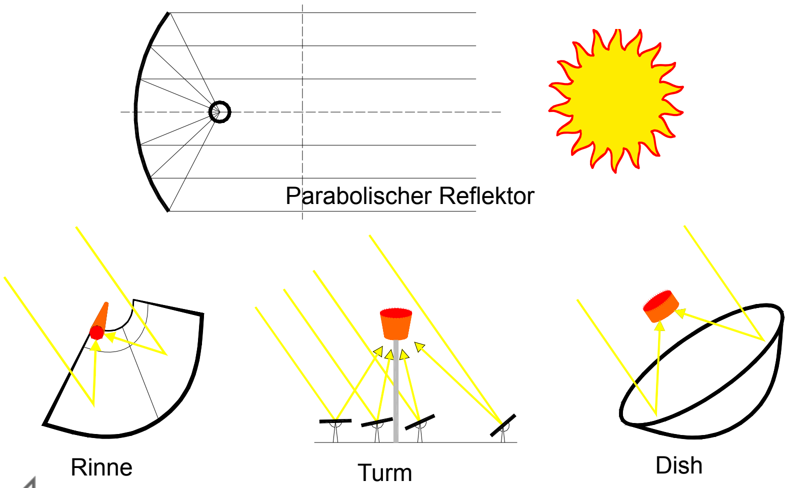
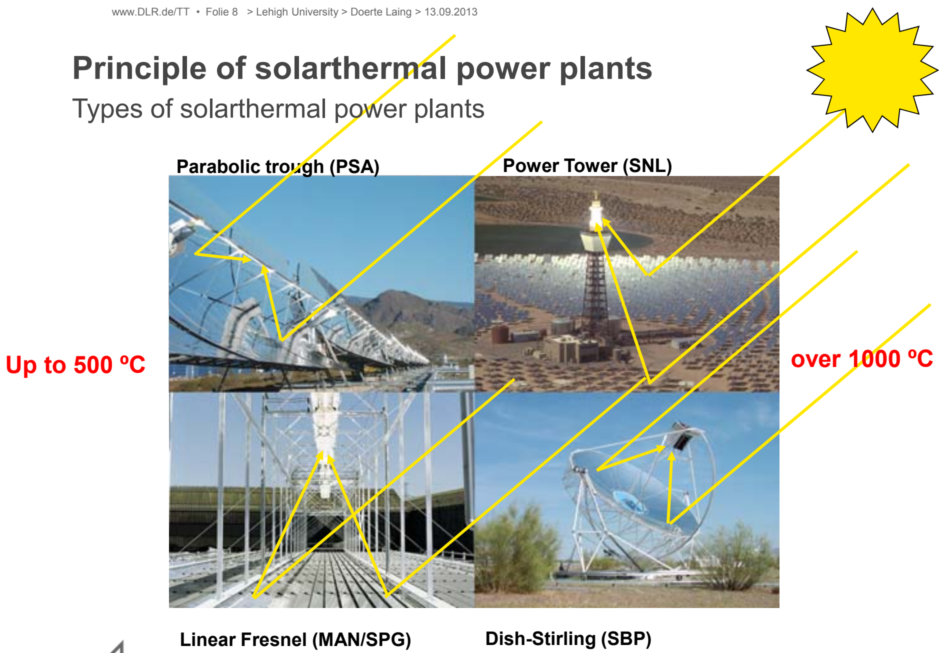
Principle of solarthermal power plants

High temperatures through concentration of solar radiation



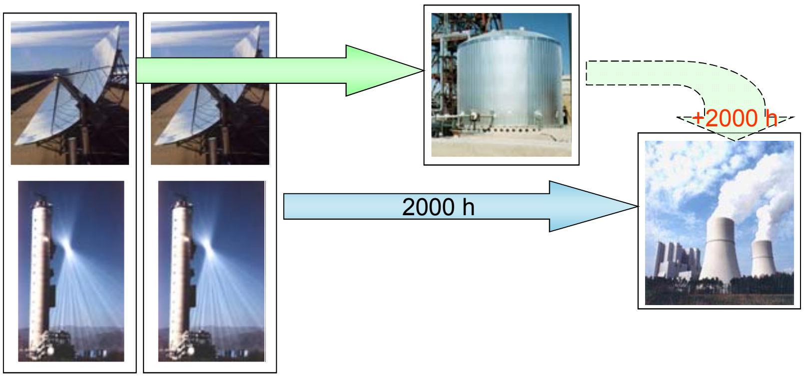
Principle of solarthermal power plants

Types of solarthermal power plants



Integration in the electricity supply system

Adaptation to electricity demand with thermal storage



Thermal Storage => more operating hours => cost reduction

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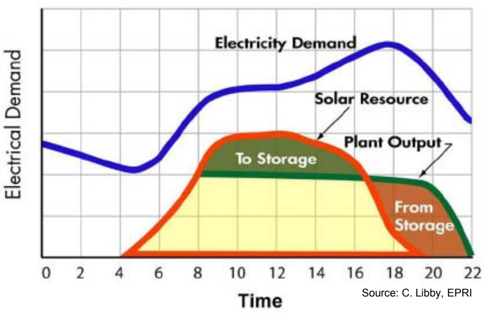
Energy Storage for Concentrating Solar Power Plants



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

→ **Energy storage necessary for successful market implementation of CSP technology**

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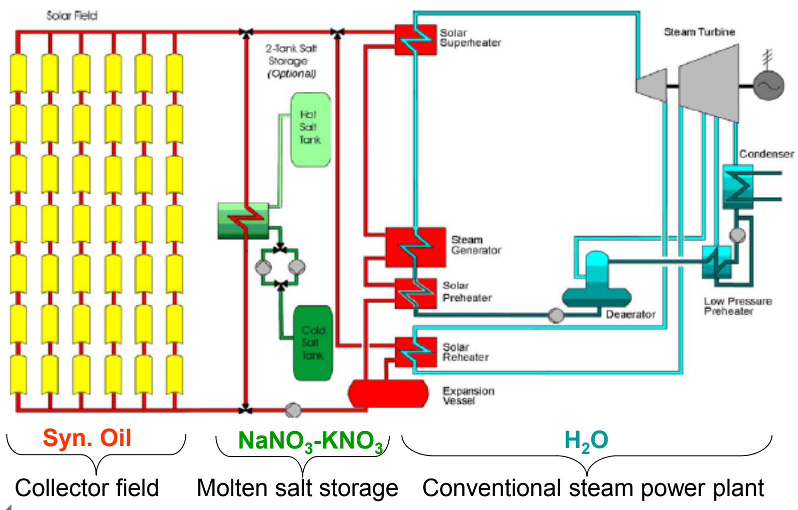
Parabolic Trough Power Plant



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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

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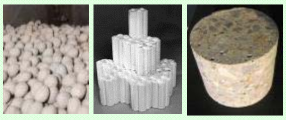
Storage Concepts

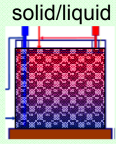
Sensible Heat

solid



liquid

solid/liquid



Latent Heat

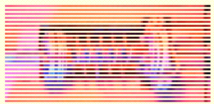
Salts solid-solid

Salts solid-liquid

Heat of Reaction

Sorption

Gas-solid reaction



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Storage Concepts

Sensible Heat

- Sensible Heat Storage 20 – 100 kWh/m³ (dependend on temperature difference)

Latent Heat

- Latent Heat Storage 50 – 150 kWh/m³ (for minimal temperature difference)

Heat of Reaction

- Thermo-chemical Storage 100 – 400 kWh/m³ (dependend on driving gradient (temperature or pressure))

Energy density [kWh/m³]: low → high

Development status: high → low

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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
- Solid media storage for Solar Tower with Air
- Latent heat - PCM storage
- Thermo-chemical storage

Future focus for CSP
- Higher plant efficiency => Increase process temperature
- New fluids: steam, molten salt, gas/air

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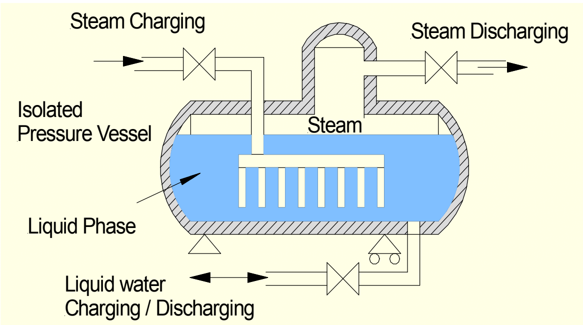
State-of-the-Art - Steam Accumulators
Storage of sensible heat in pressurized liquid water



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

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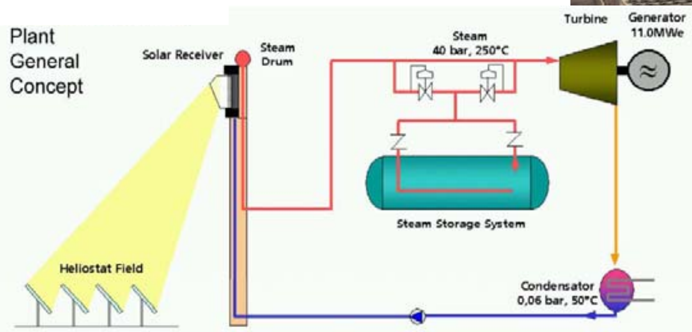
State-of-the-Art - Steam Accumulators
PS10

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

Source: Abengoa Solar



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State-of-the-Art - Steam Accumulators
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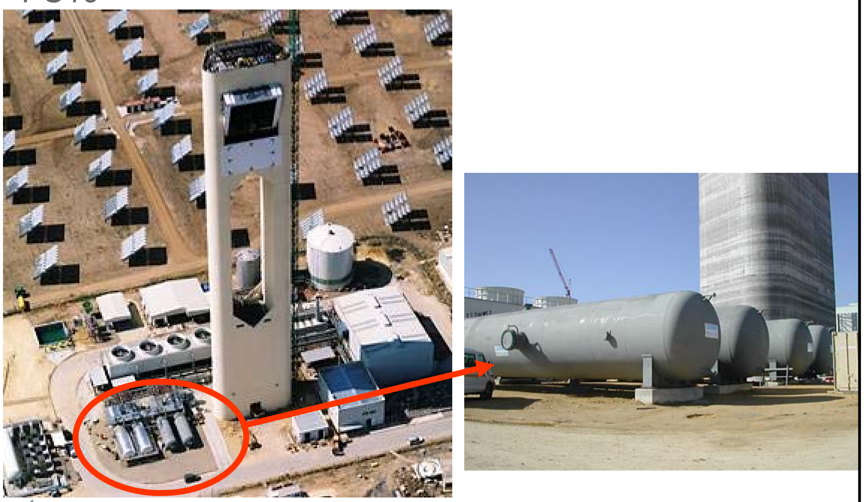

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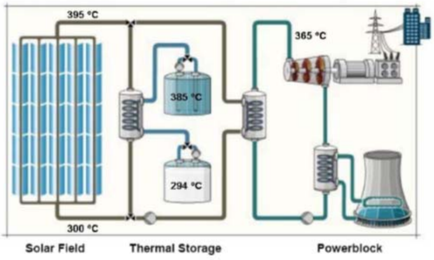
State-of-the-art - Molten salt storage
Indirect 2-Tank Storage

Andasol

- Storage capacity 1010 MWh (7.7h)
- Nitrate salts
  (60% $NaNO_3$ + 40% KNO_3)



- 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.

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Parabolic trough power plants with thermal oil
ANDASOL 1: 50 MWe, 7.7 hours storage capacity

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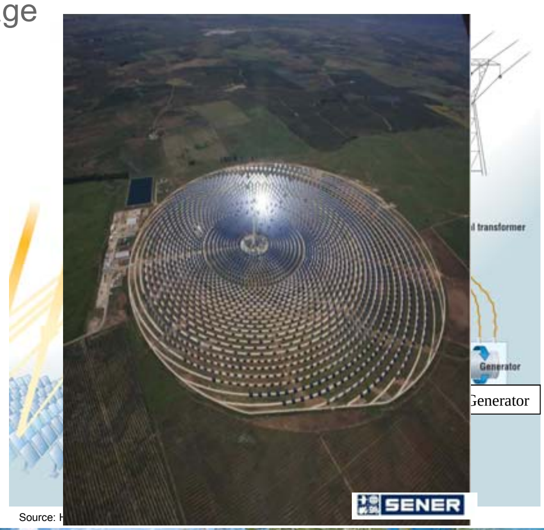
State-of-the-art - Molten salt storage
Direct 2-Tank Storage

- 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*



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- Thermo-chemical storage

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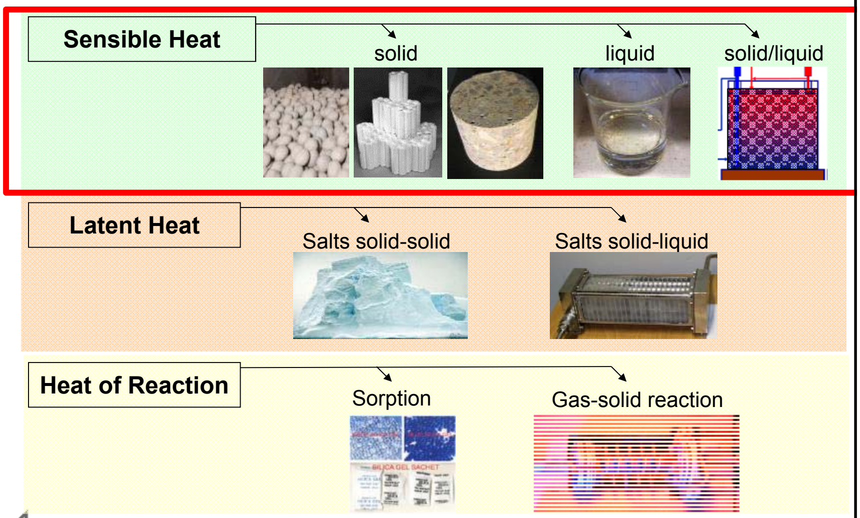
Storage Concepts – Sensible Heat Storage



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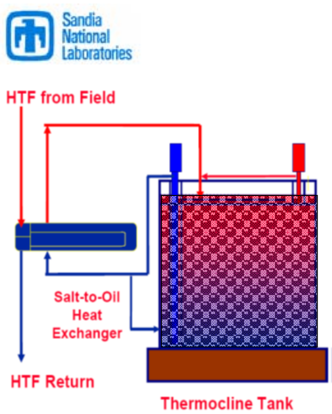
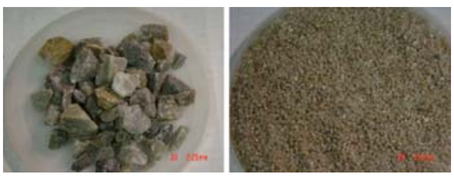
Molten Salt Storage
Current Developments – Thermocline concept



- Most of the salt volume is replaced by a low cost solid filler material
- Molten Salt is stored in one tank → Cost Reduction



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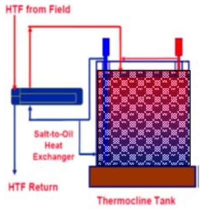
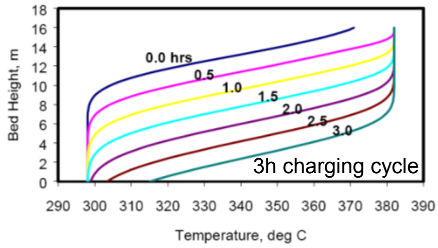
Molten Salt Storage
Current Developments – Thermocline concept

Status:
- Most solids react with molten salt
- Thermal ratcheting can occur
- No long term experience have been published so far
- Cost reduction potential: approx. 33 %
- Lots of simulation research has been done
- Test loop with test module is in the design stage at DLR





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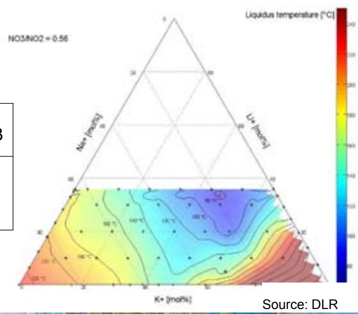
Molten Salt Storage
Current Developments – New Salt Mixtures

- 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



Source: DLR

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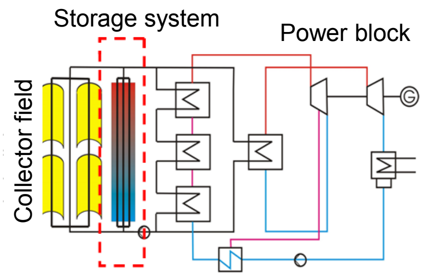
Alternative Storage Technology for Trough Plants with Oil HTF – Concrete Storage

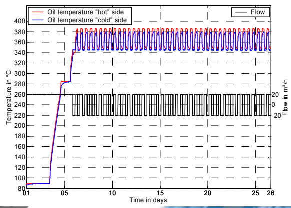


- Heat transfer fluid and storage medium are different
- Low cost storage material with integrated heat exchanger
- No risk of solidification
- Modular and scalable design
- Economic and reliable TES (< 35 € / kWh TES capacity)
- Flexible to large no. of sites and construction materials

Concrete Storage
Set-up

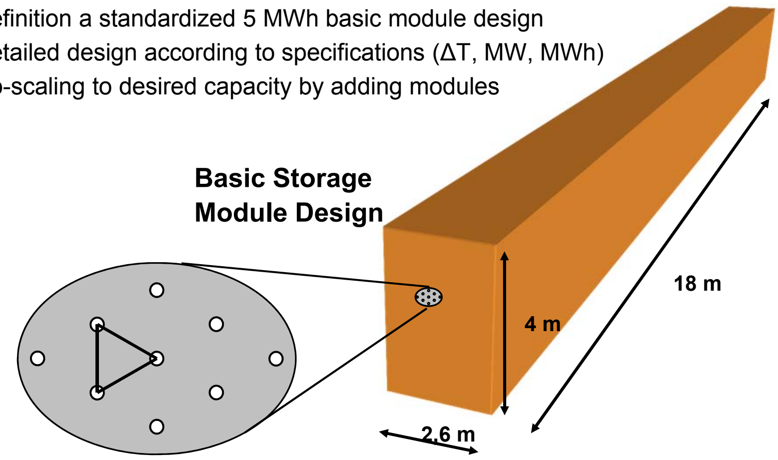
Concrete Storage
Status

- 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

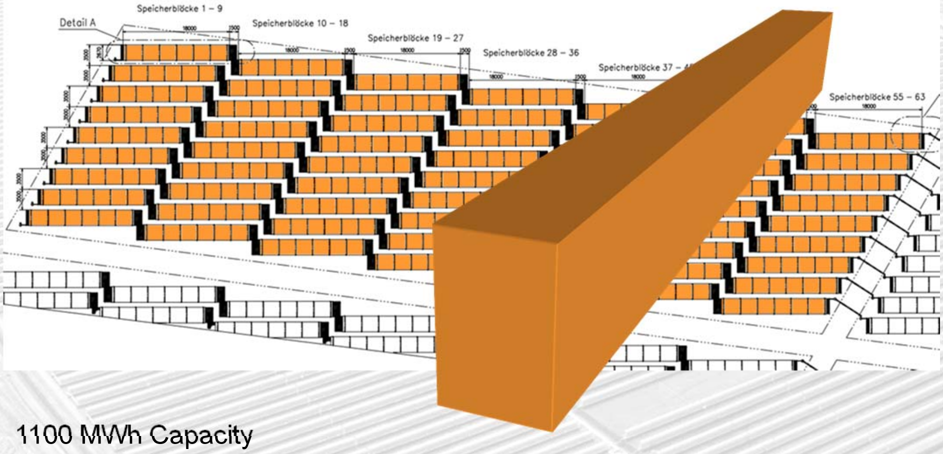


Concrete Storage
Strategy for commercialization

- 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



1100 MWh Capacity
Configuration of 4 x 63 = 252 modules

Concrete Storage
Layout for trough plant of Andasol type

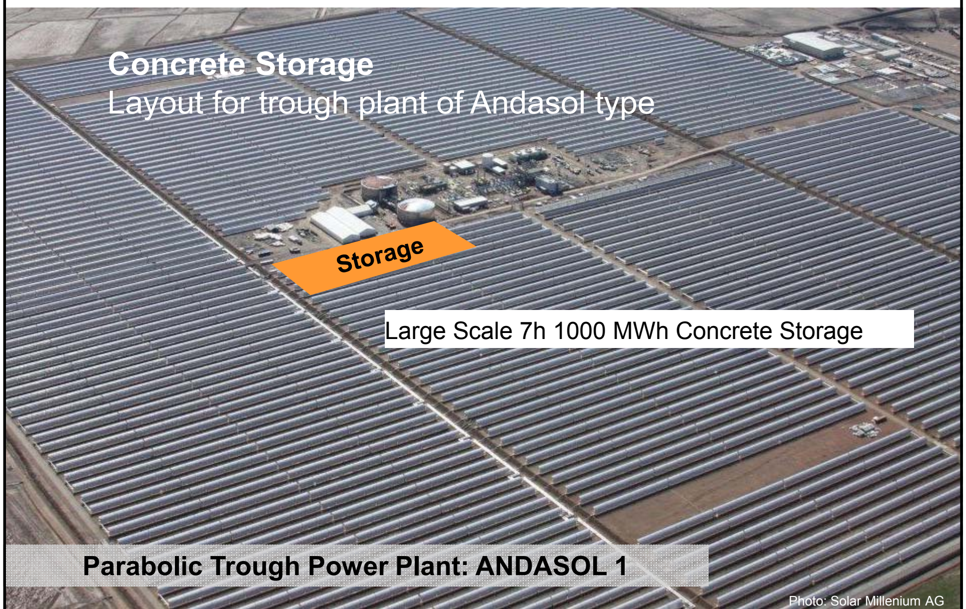
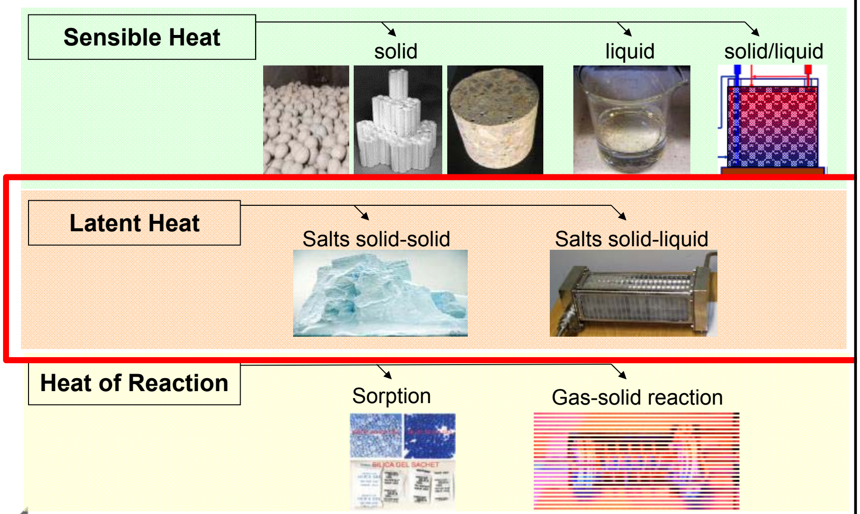


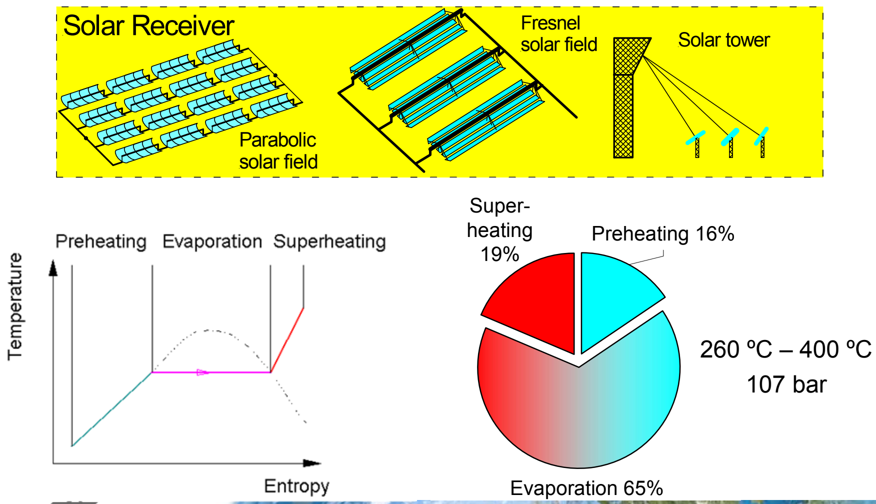
Photo: Solar Millenium AG

Storage Concepts – Latent Heat Storage



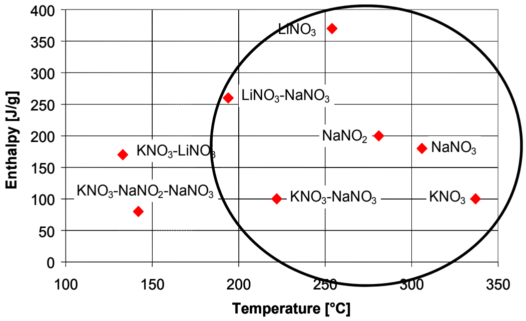
Storage Systems for DSG Plants

Latent Heat Storage

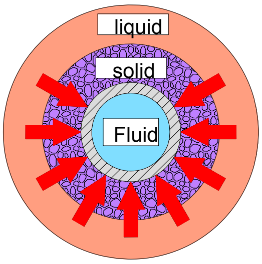


Latent Heat Storage
Features of PCM (phase change material) Storage

- 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
Challenge

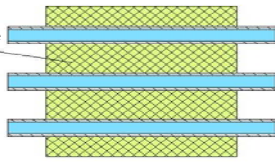


Heat transfer coefficient is dominated by the thermal conductivity of the solid PCM
→ Low thermal conductivity is bottleneck for PCM

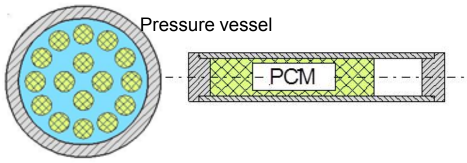
Latent heat storage
Approaches for heat transfer enhancement

Composite material

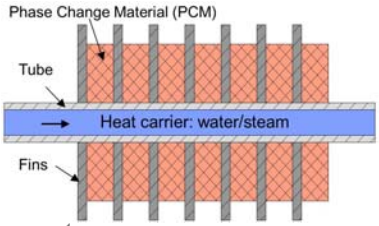
PCM/graphite composite



Macro encapsulation



Extended heat exchanger structure



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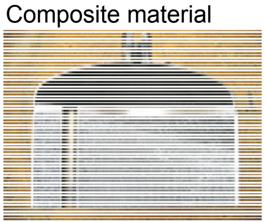
Latent heat storage
Approaches for heat transfer enhancement

Composite material



PCM/graphite composite

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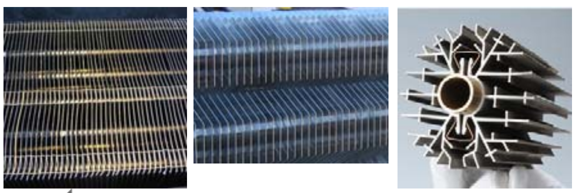

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Status of Latent Heat Storage


Source: DLR


Source: DLR

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 °C

Experimental validation

- 6 test modules with 140 – 14,000 kg PCM

Storage System for DSG
Latent heat storage for evaporation


Source: DLR

PCM-Evaporator module:

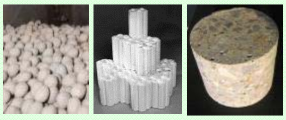
- PCM: NaNO3
- Melting point: 306 ° C
- Salt volume: 8.4 m³
- Total height 7.5 m
- Inventory ~ 14 t
- Capacity ~ 700 kWh

⇒ Worlds largest high temperature latent heat storage with 14 tons of $NaNO_3$ (700 kWh) tested in 2010 / 2011 with 2949 h, 95 cycles

Storage Concepts – Thermo-chemical Heat Storage

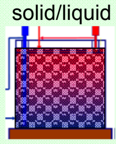
Sensible Heat

solid



liquid

solid/liquid



Latent Heat

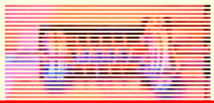
Salts solid-solid

Salts solid-liquid

Heat of Reaction

Sorption

Gas-solid reaction



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Thermo-chemical Heat Storage

Gas-Solid Reactions – Principle and Potential

$$A+B \rightleftharpoons AB + Heat$$

Thermo-chemical heat storage

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Thermo-chemical Heat Storage
Gas-Solid Reactions – Principle and Potential

A+B ⇄ AB + Heat

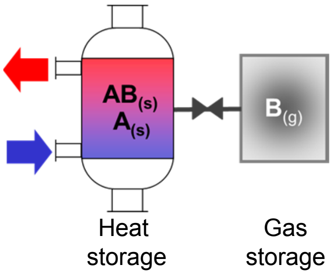
Thermo-chemical heat storage

- Reversible gas-solid reactions
- Utilization of enthalpy of reaction

endothermal

$$AB_{(s)} + \Delta H \rightleftharpoons A_{(s)} + B_{(g)}$$

exothermal



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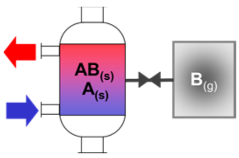
Thermo-chemical Heat Storage
Gas-Solid Reactions – Principle and Potential

Potential:
- High storage densities
- Loss-free and long-term storage
- Detachment of storage capacity and thermal power
- Possibility for heat transformation
- Application in a wide temperature range (below ambient up to 1000°C)

A+B ⇄ AB + Heat

Thermo-chemical heat storage



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Thermo-chemical Heat Storage
Calcium Hydroxide as Storage Material

- Known reaction system
- Gaseous reactant: steam
- Low cost basic material (limestone)
- High reaction enthalpy ~ 100 kJ/mol

- Cycle stability needs to be proven
- Process engineering needs to be simplified

- Theoretical storage densities:


Limestone Quarry Hahnstetten

T_{EQ} [1 bar]	ΔH [1 bar]	Storage Density*		
		Solid only	Solid + H_2O	Mass related
° C	kJ/mol	kWh/m³	kWh/m³	kWh/t
507	100	410	323	373

** Porosity of 0.5*

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Thermo-chemical Heat Storage
Test facility - 10 kW, T_{max} = 1000 °C


Quelle: DLR

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Electrically heated latent heat storage

Problem: Increasing amount of renewable energy are challenging the grid

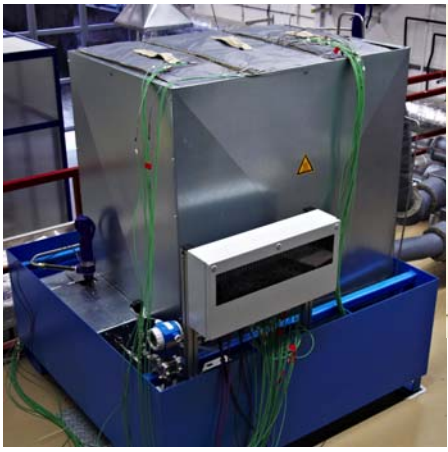
Idea: store „surplus“ electricity from renewable energies as high temperature heat

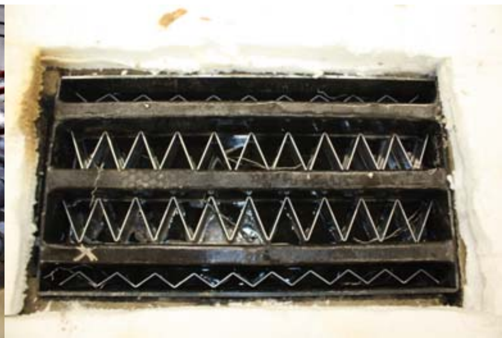
⇒Use for process heat applications in industry (e.g. bakeries)
(„inversing the concept of the night storage heaters“)

Storage concept:

- Latent heat storage with sodium nitrate (T_melt = 305 ºC)
- Apply new design with plate heat exchanger
- Directly charge PCM with special resistance heater
- Discharge of PCM through plate heat exchanger with air or thermal oil

Latent Heat Storage – Plate Heat Exchanger Design





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
- Thermo-chemical storage development is in a basic research stage
- Continuous research and development effort is needed especially for higher process temperatures (> 400°C) and for further cost reduction
- High temperature storage also needed for energy efficiency in industrial processes and grid stability with increasing share of renewables

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Thank you for your attention!

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Wissen für Morgen

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