Advanced Concentrating Thermal Technologies for Power and Process Heat Generation

Robert Pitz-Paal

DLR

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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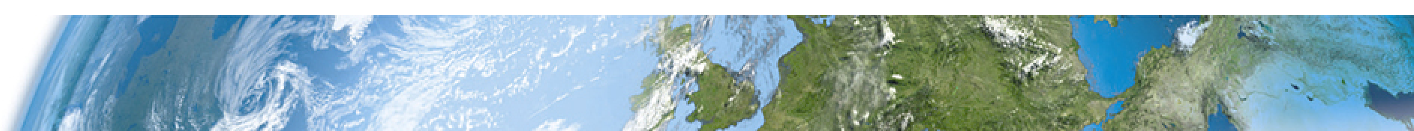
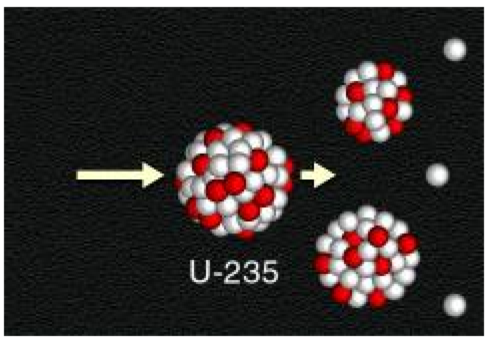
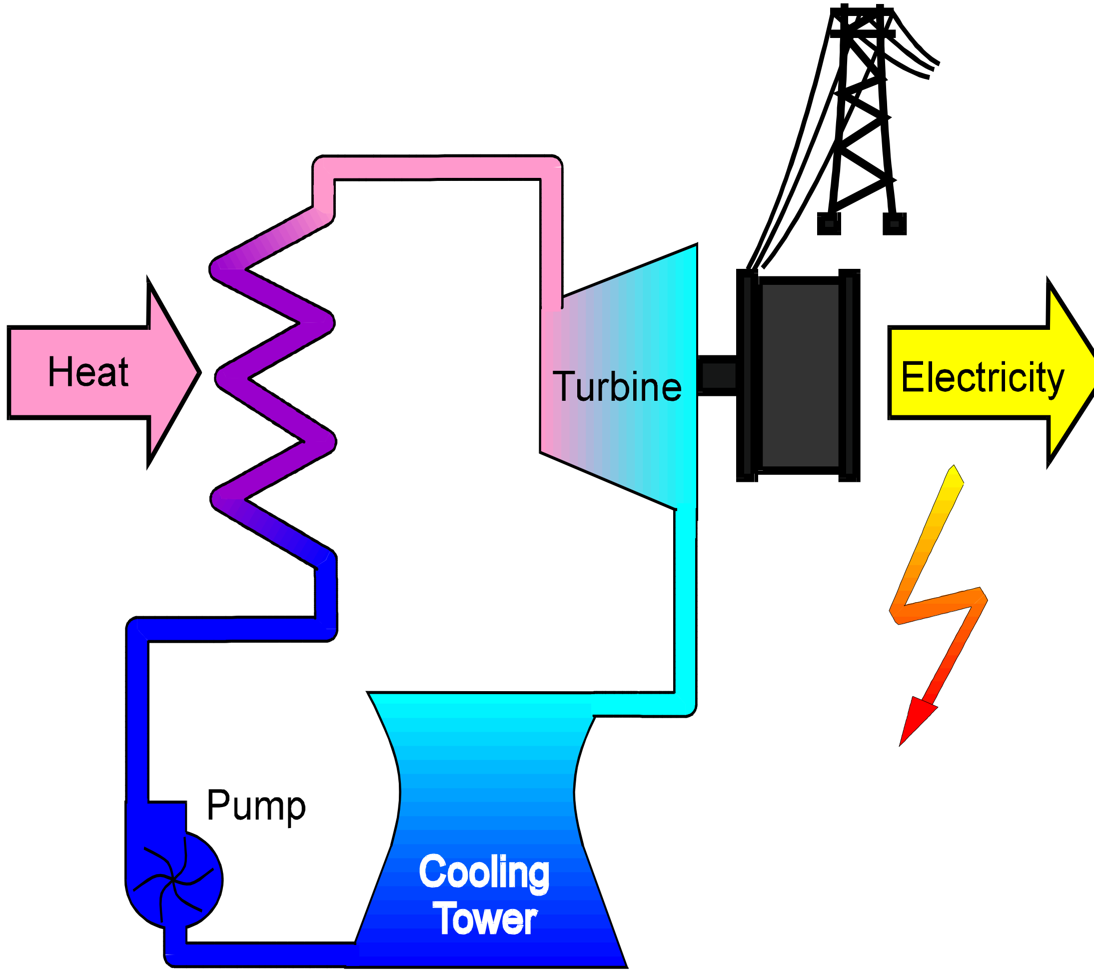


What is CSP?



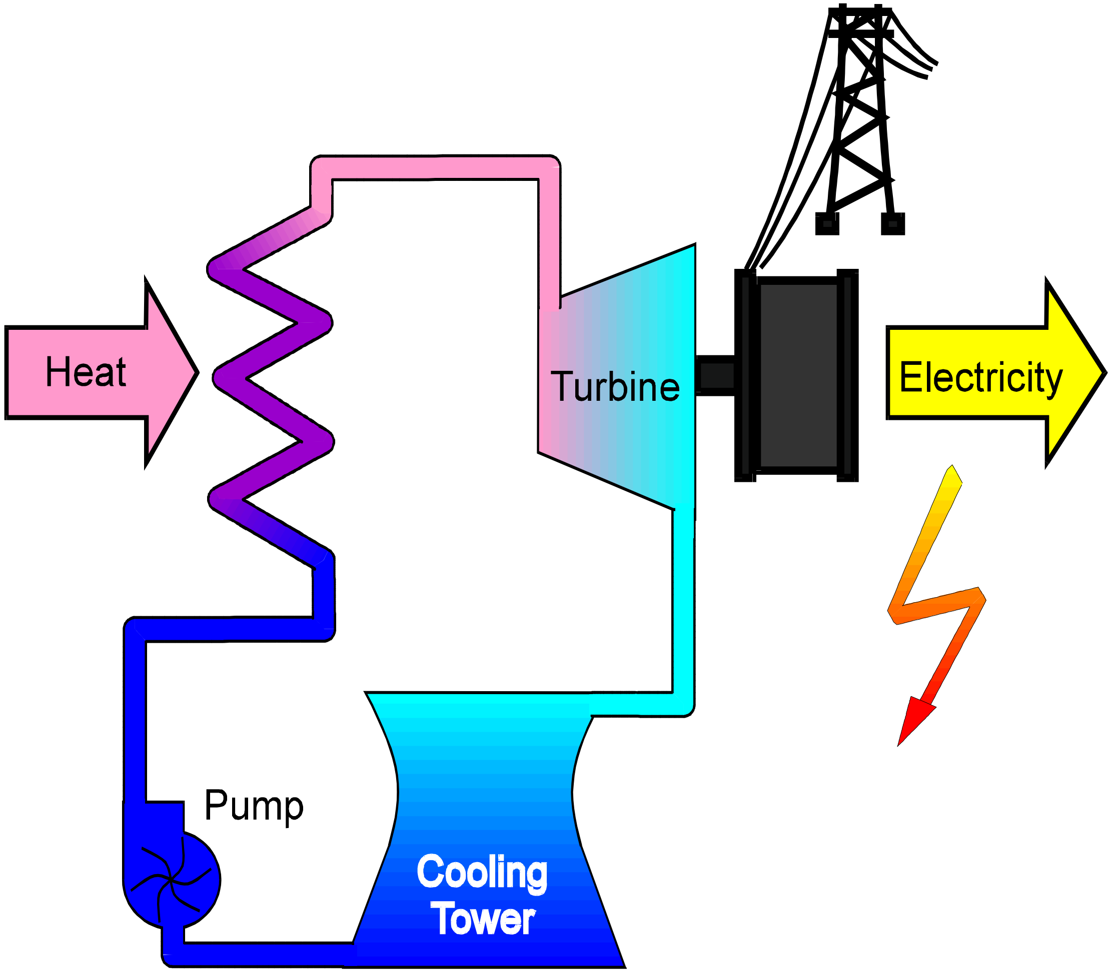
Conventional power plant



DLR.de • Chart 5

What is CSP?


Concentrating solarpower plant



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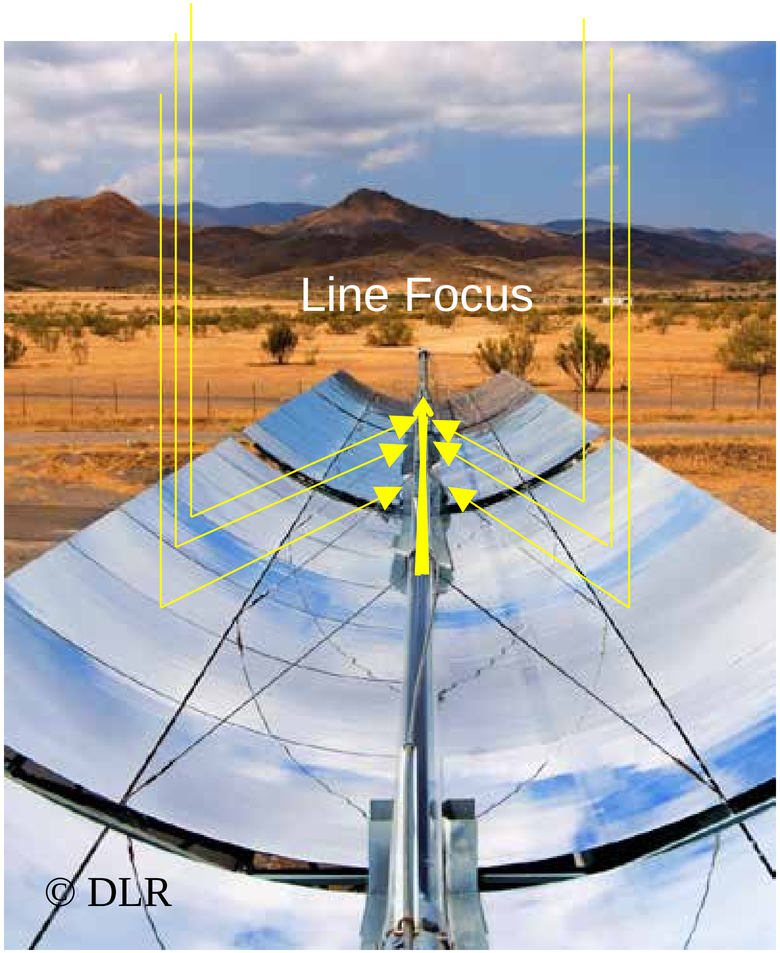
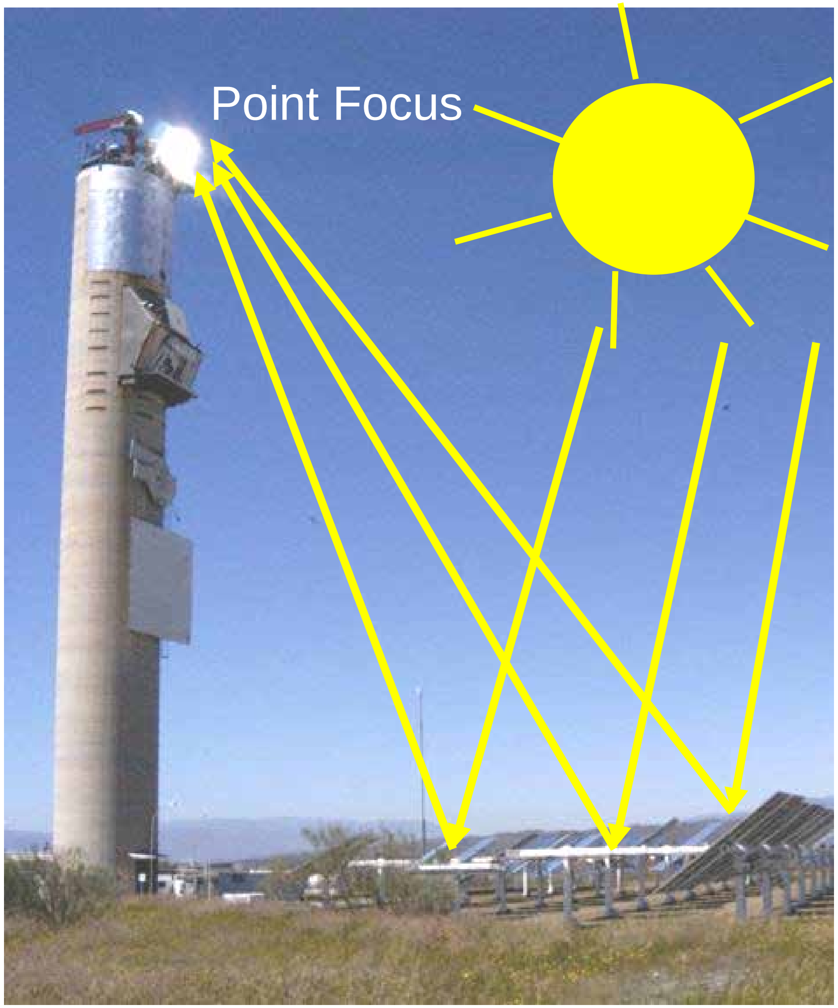
Trough vs. Tower

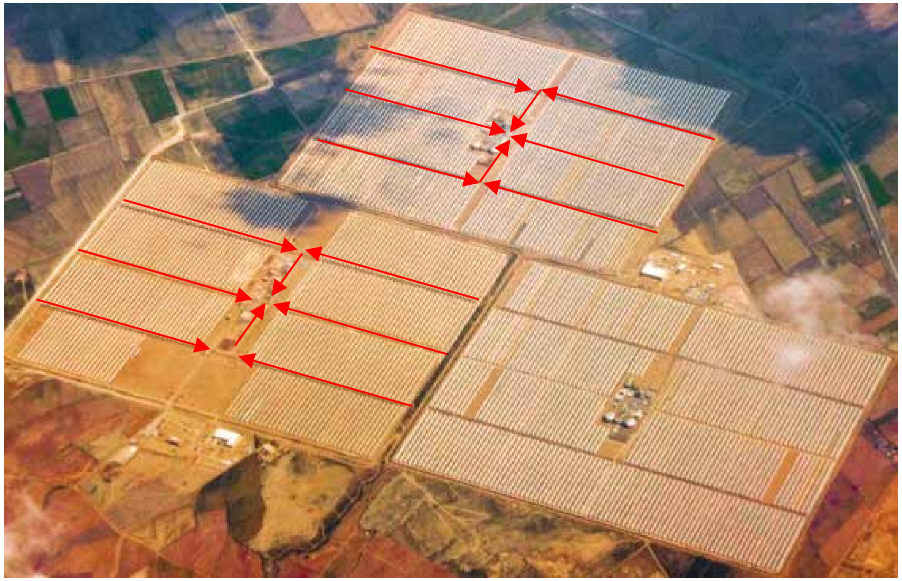




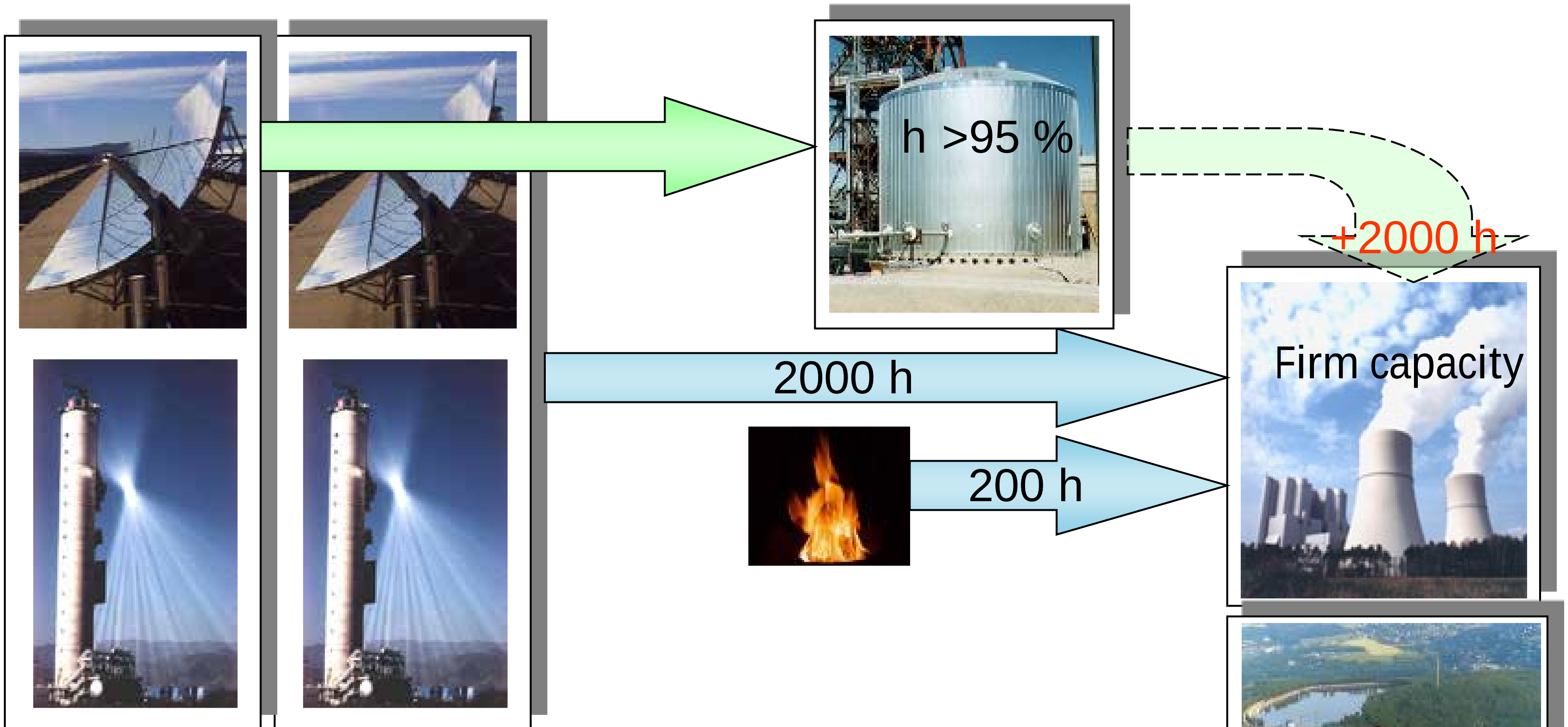
Trough vs. Tower

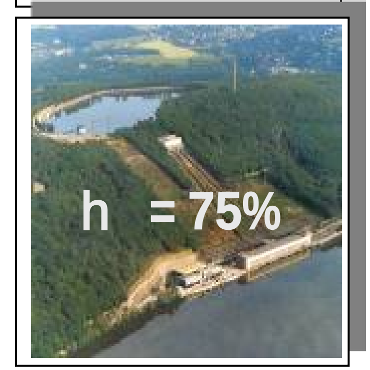
- Solar energy collected by reflection

- Solar energy collected by piping



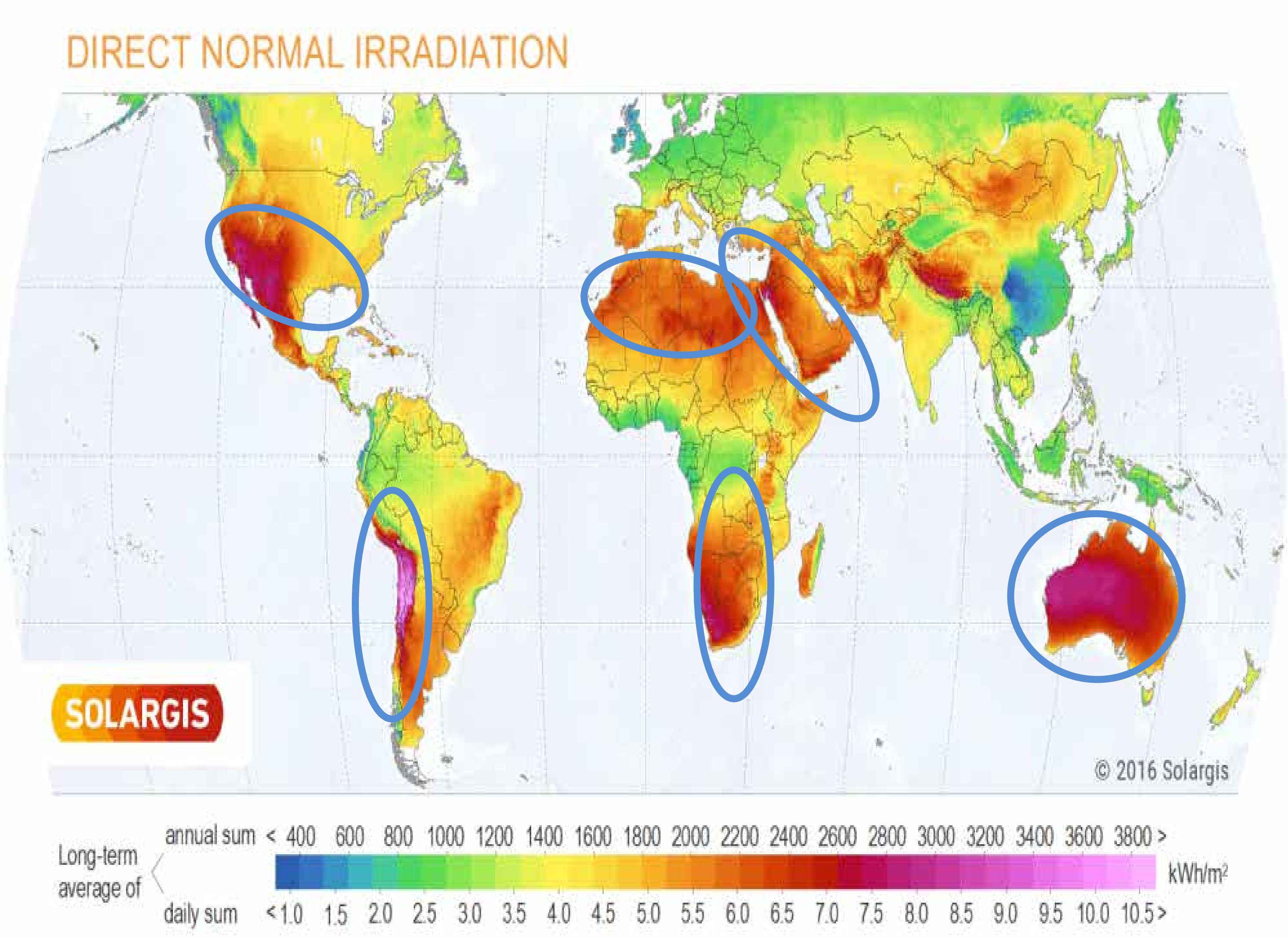
Thermal Storage vs. Electric Storage





CSP with thermal storage and fossil back provides reliable dispatchble power at no additional cost

CSP only suitable in areas with high direct normal radiation



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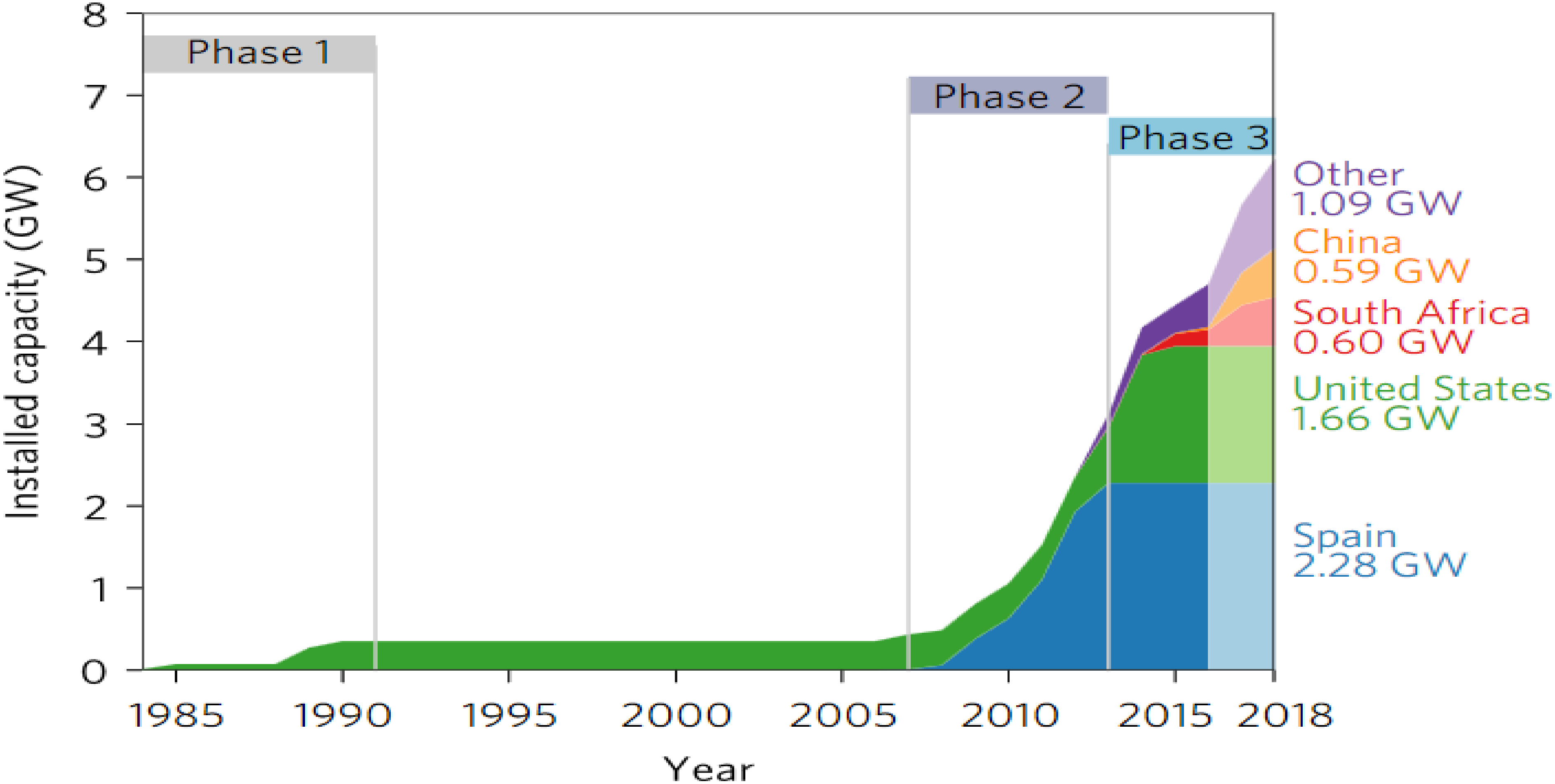
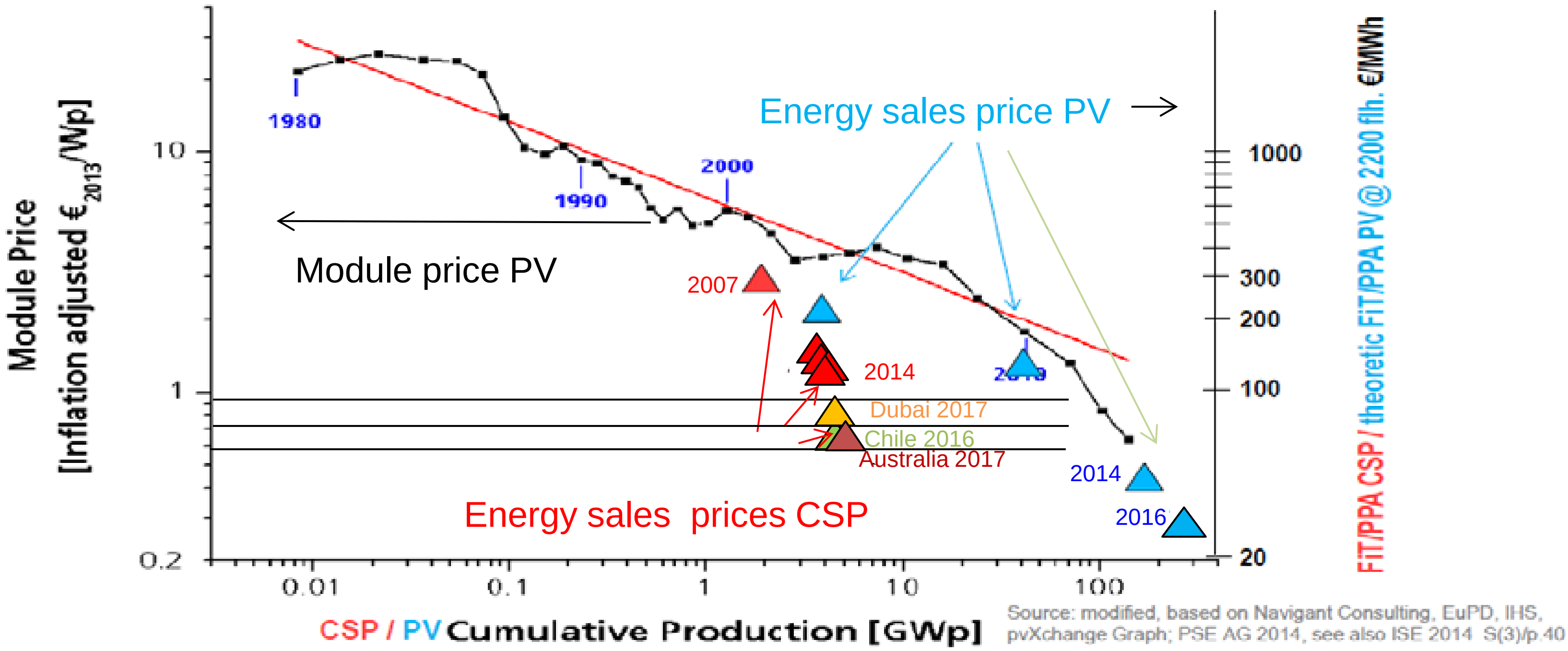
Global expansion of CSP in three phases

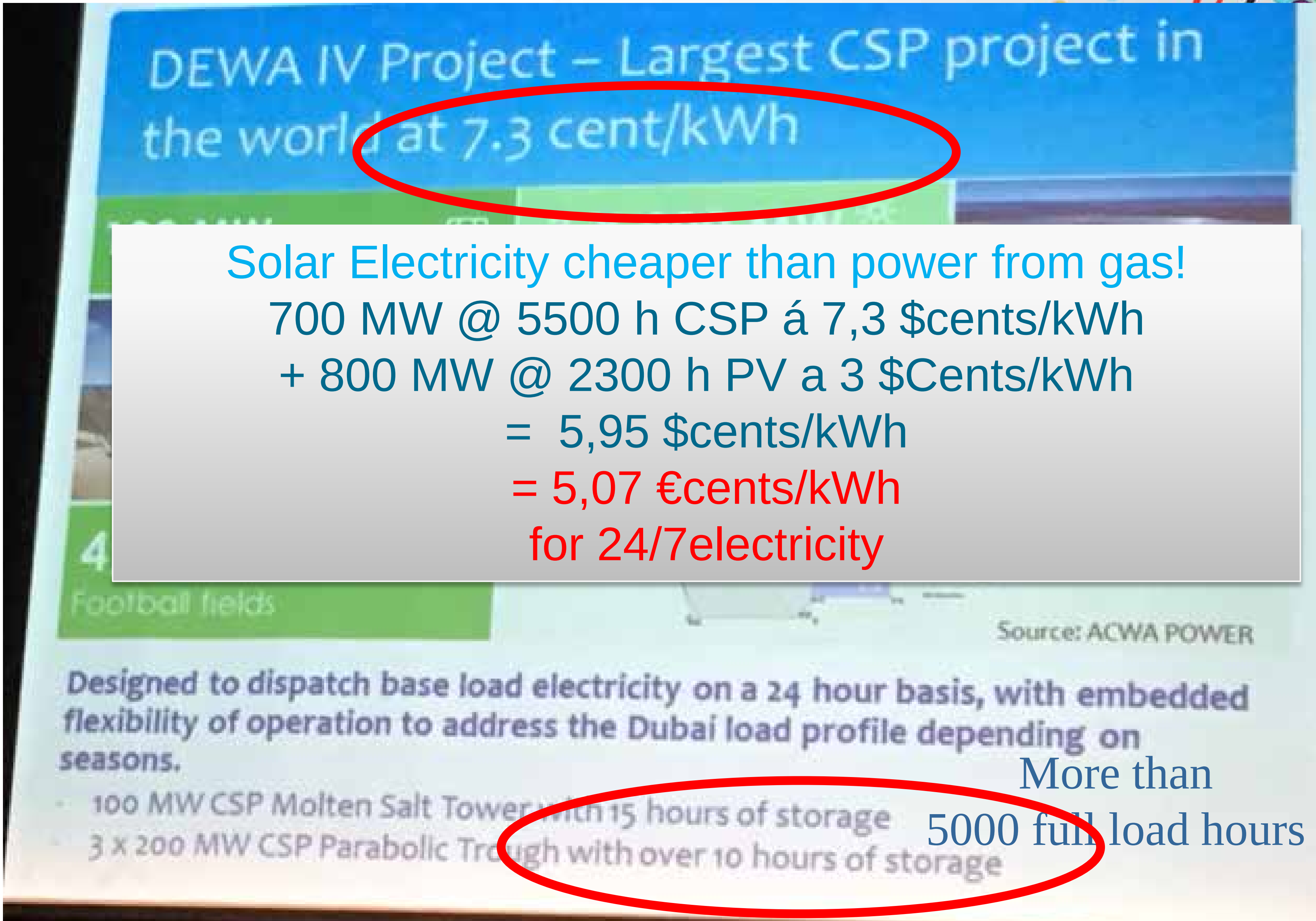


Lilliestam, J., Labordena, M., Patt, A. & Pfenninger, S.
Nat. Energy **2,** 17094 (2017).

Cost for CSP and PV have dropped dramatically

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





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 24/7electricity

More than 5000 full load hours

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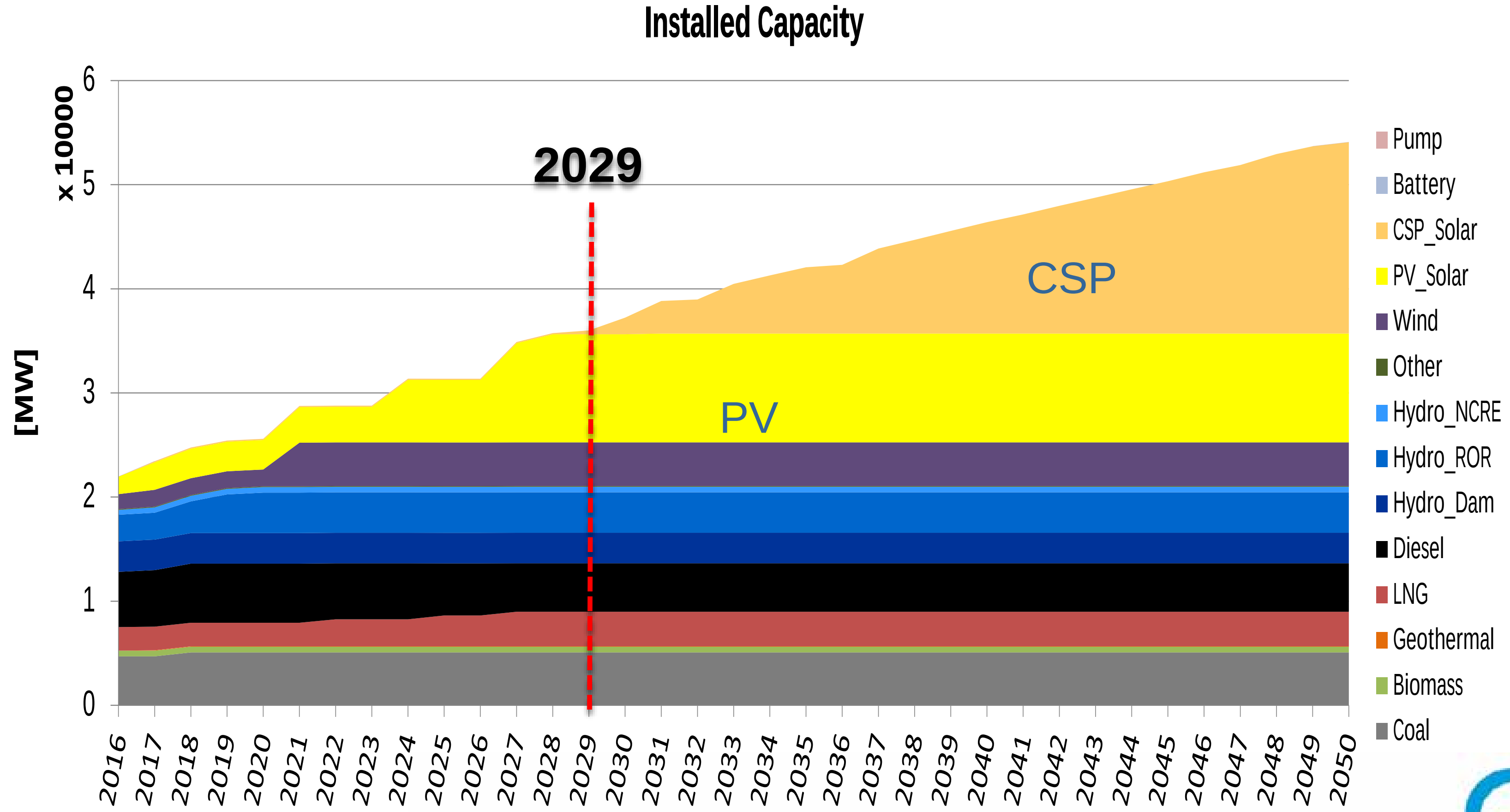
Chile Scenario Results – Expansion Model Scenario 1

	Social acceptance	Energy demand	Technological change in BESS	Externality costs	RE investment costs	Fossil fuel costs	**CSP LCOE**
Scenario B	High	High	Low	High	Low	High	**USD 50 /MWh by 2025**



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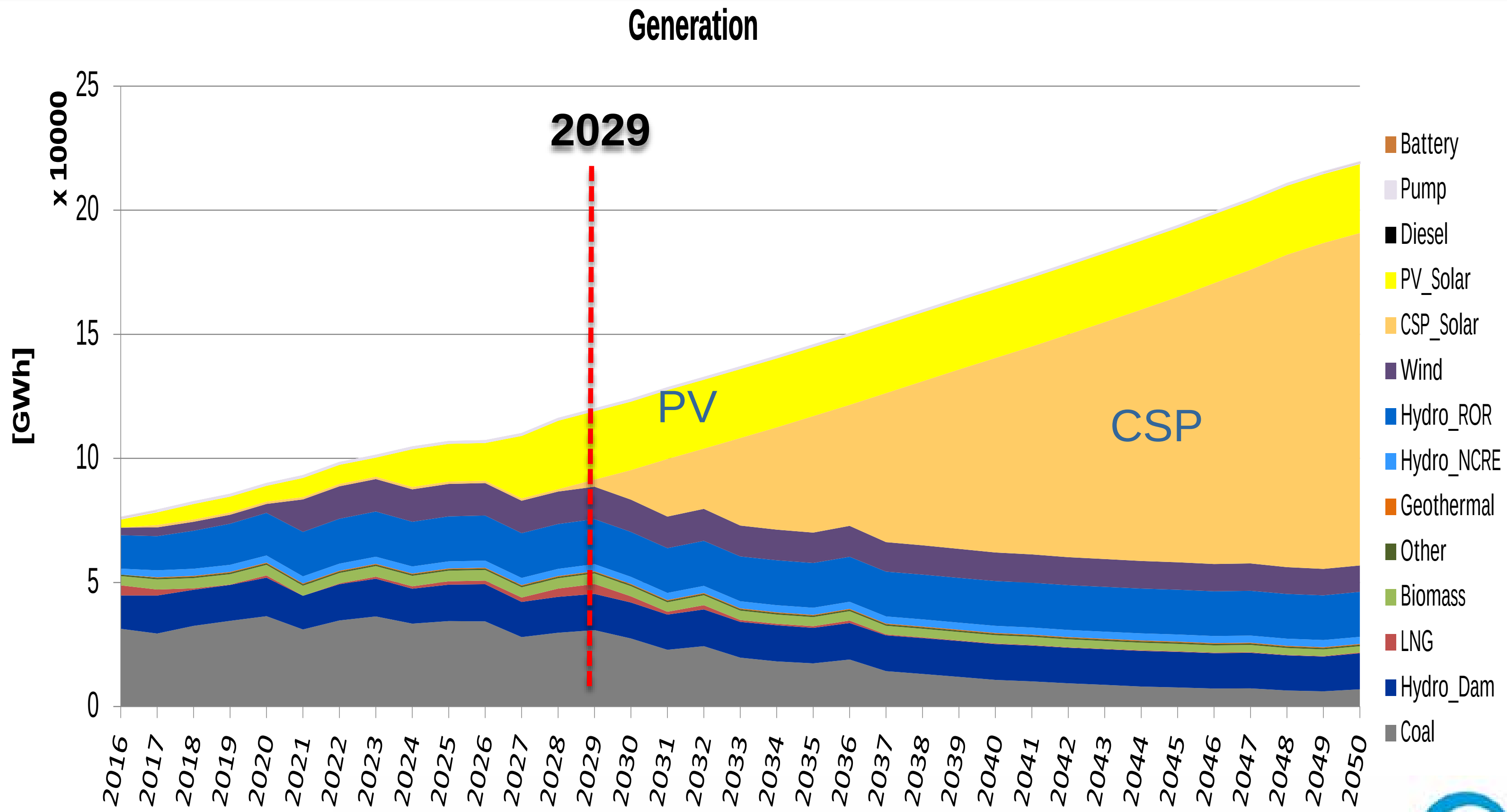
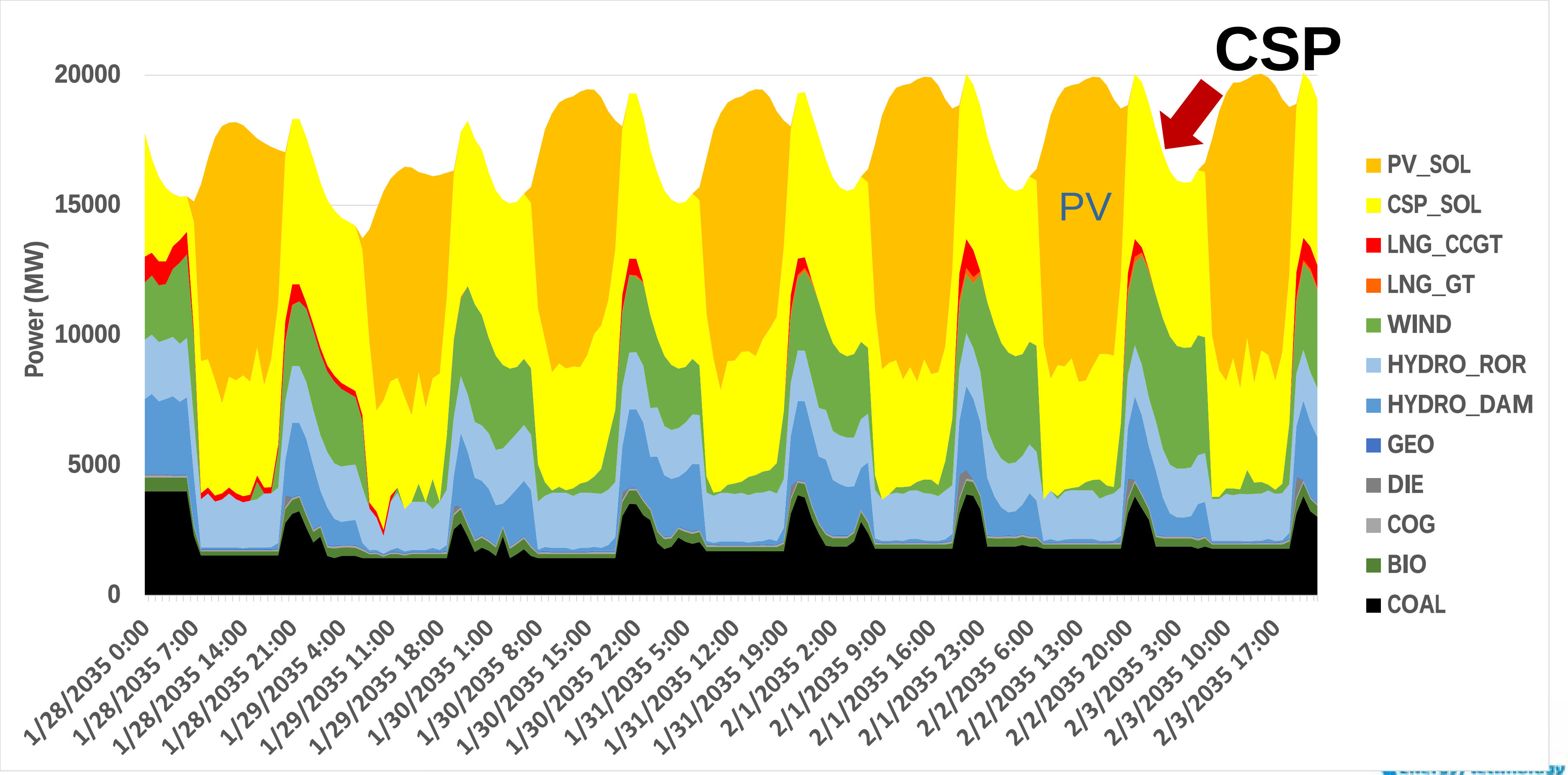


Chile Szenario results: Short Term Simulation

2035 summer week dispatch by technology



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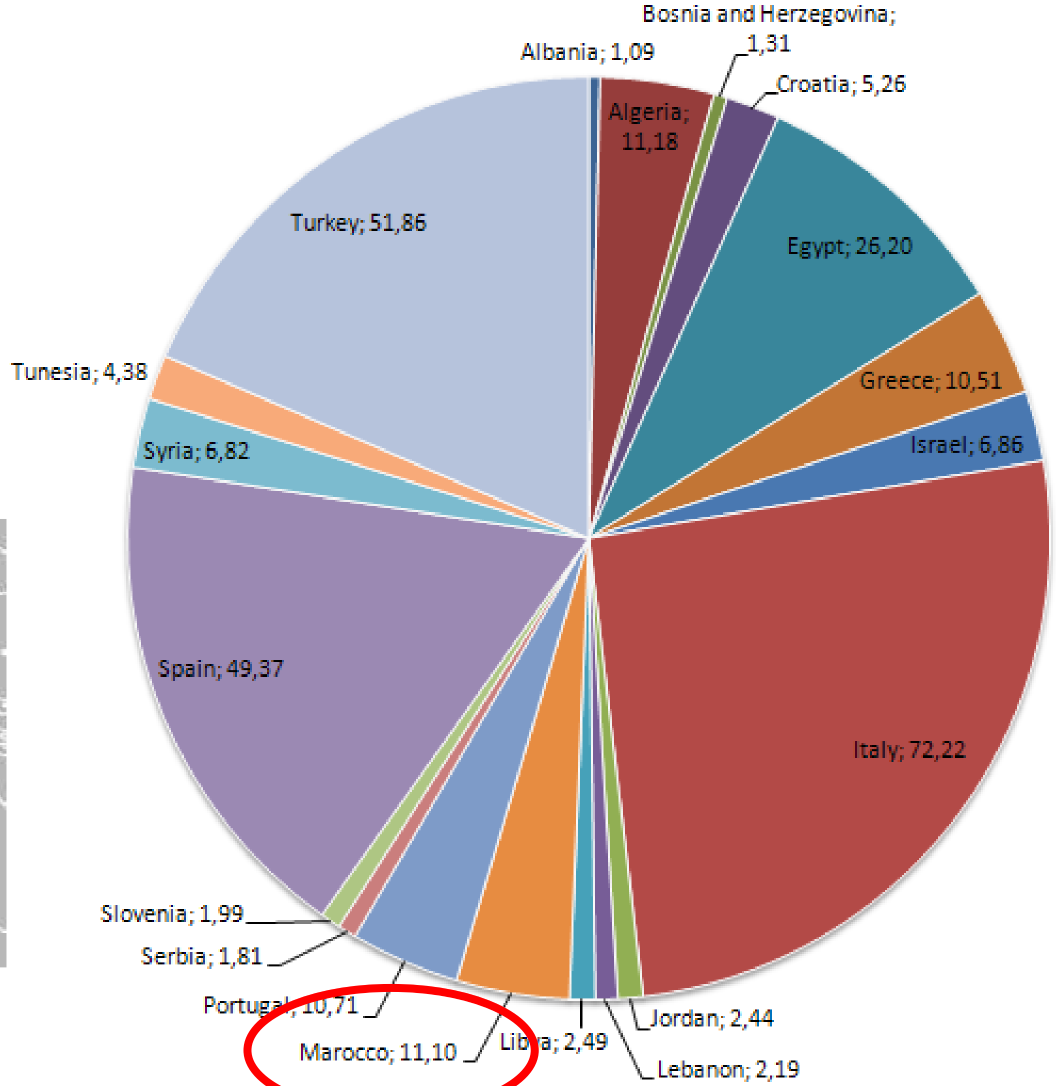
Process Heat Demand in Mediterranean Countries

Total Process Heat Demand
280 TWh/a
after 20 % energy savings



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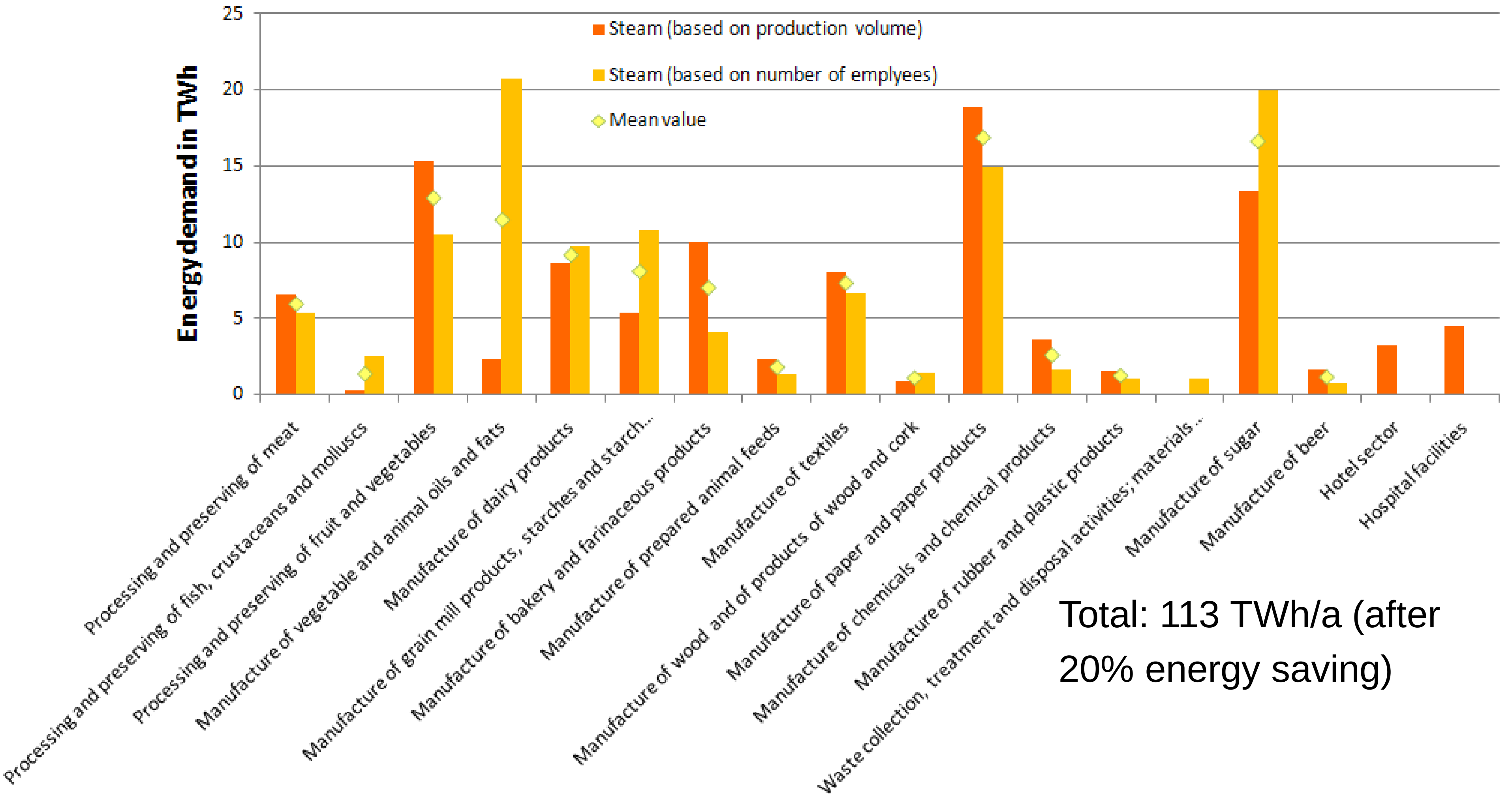
Process Steam Demand by Industry Sectors



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, Switherland

- **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

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

Economic Key Results	Base Case	6% Interest	100% Equity	
Payback Time	2.3	2.7	4.8	Years
Internal Rate of Return (IRR)	52	47	23	%
Levelized Heat Cost	41.4	41.4	41.4	€/MWh_{th}

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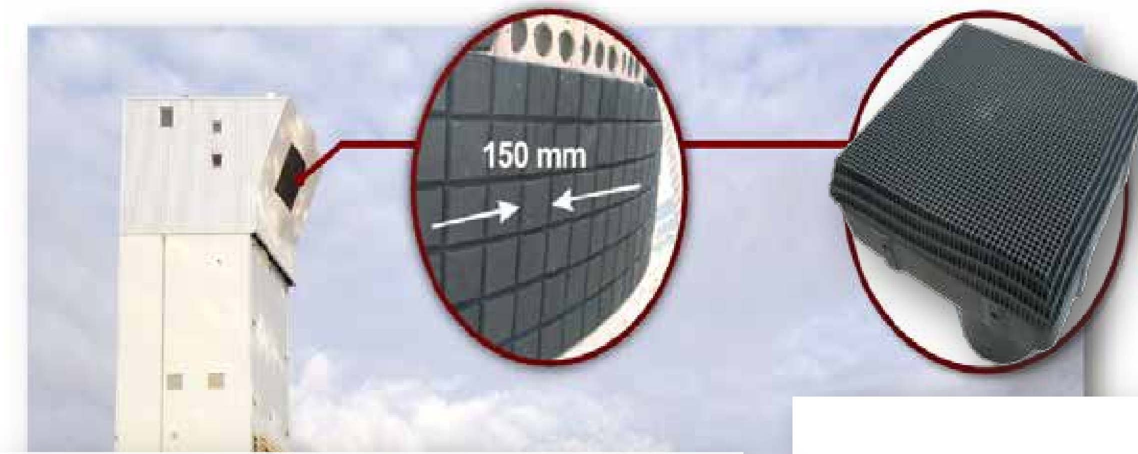
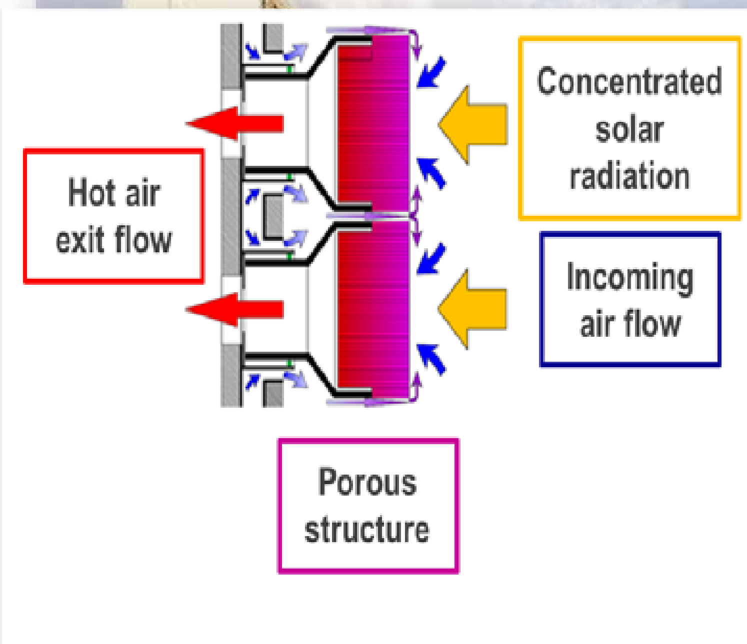
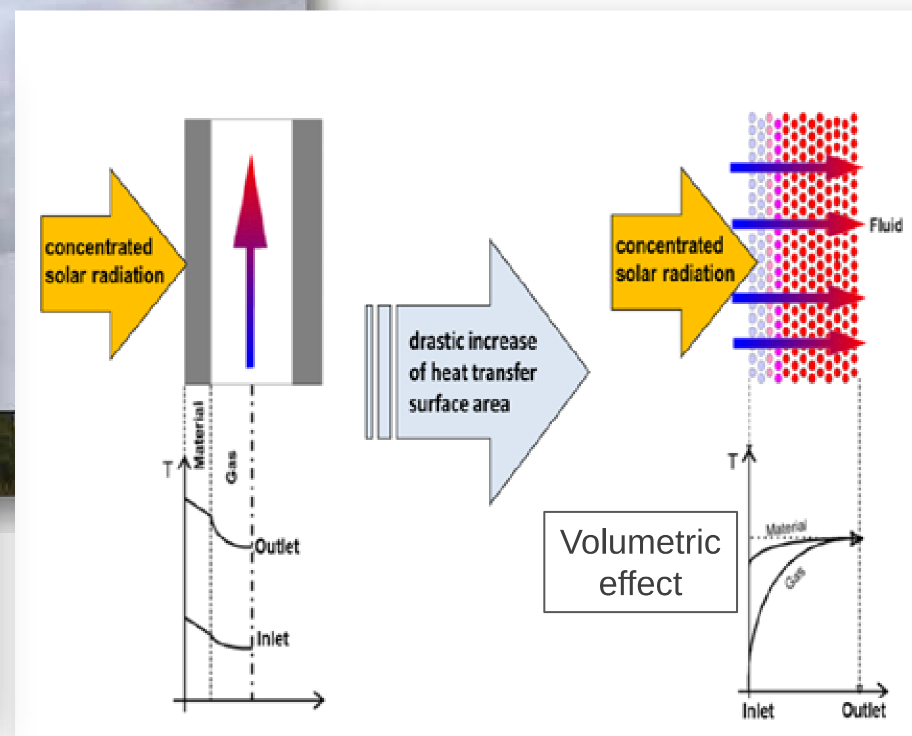
Energy from the sun: Open volumetric solar receiver



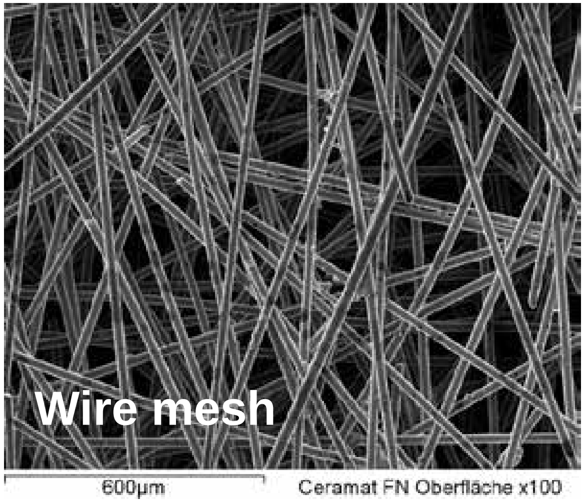
HiTRec-II
SiSiC
honeycomb

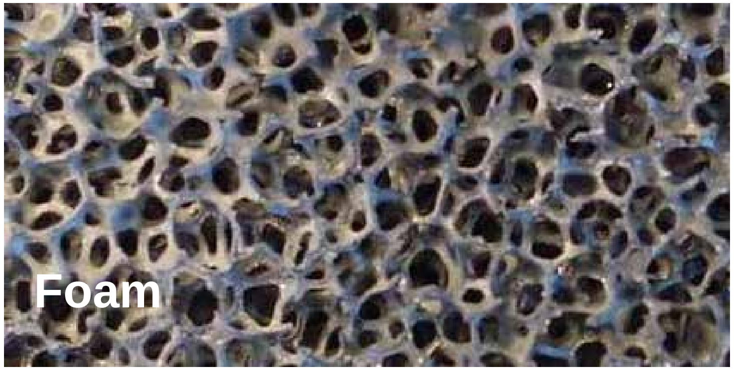




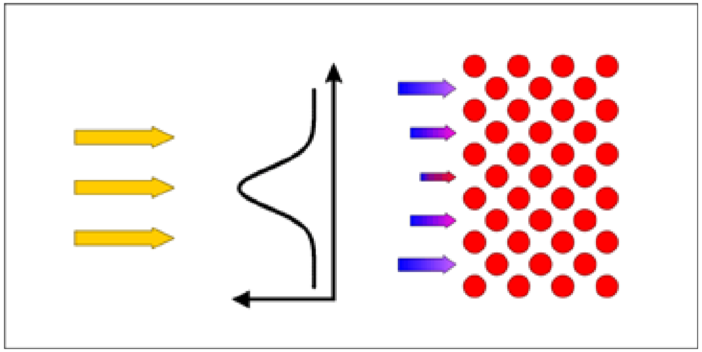
Source: dlr.de

What is the perfect absorber?





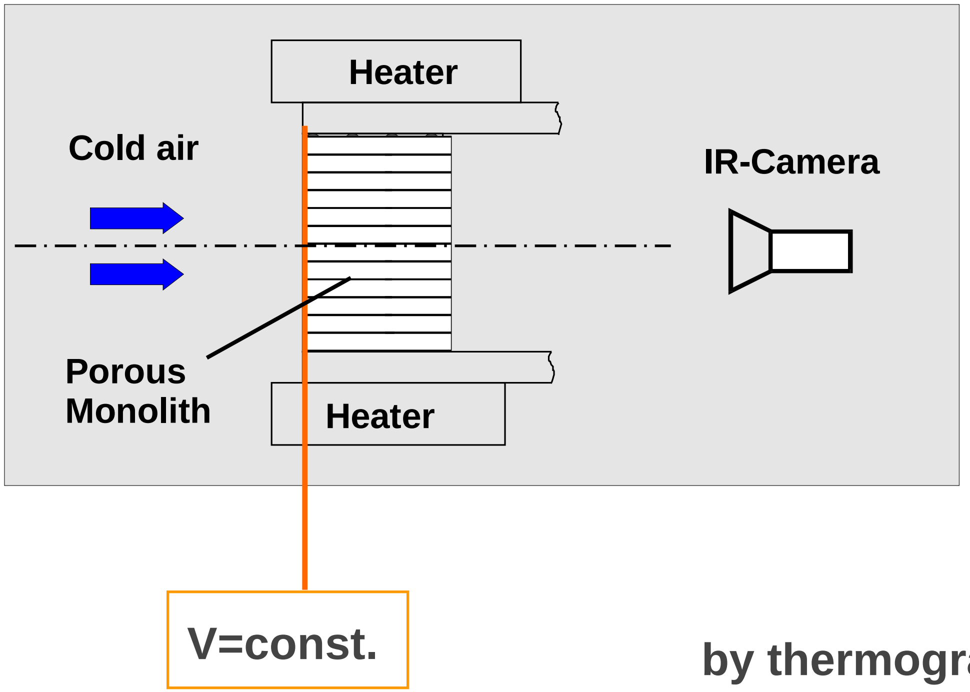
Different Characteristics affecting Flow Stability

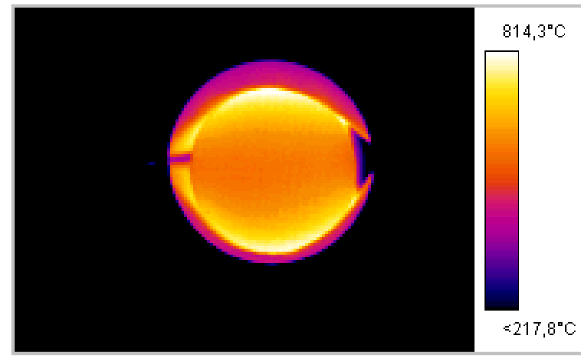


- viscosity increases with increasing temperature
- hot zones are badly cooled

- 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

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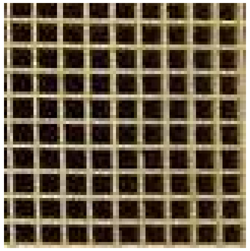
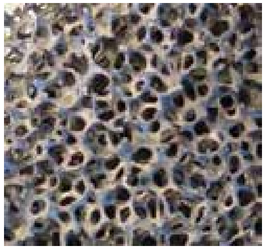
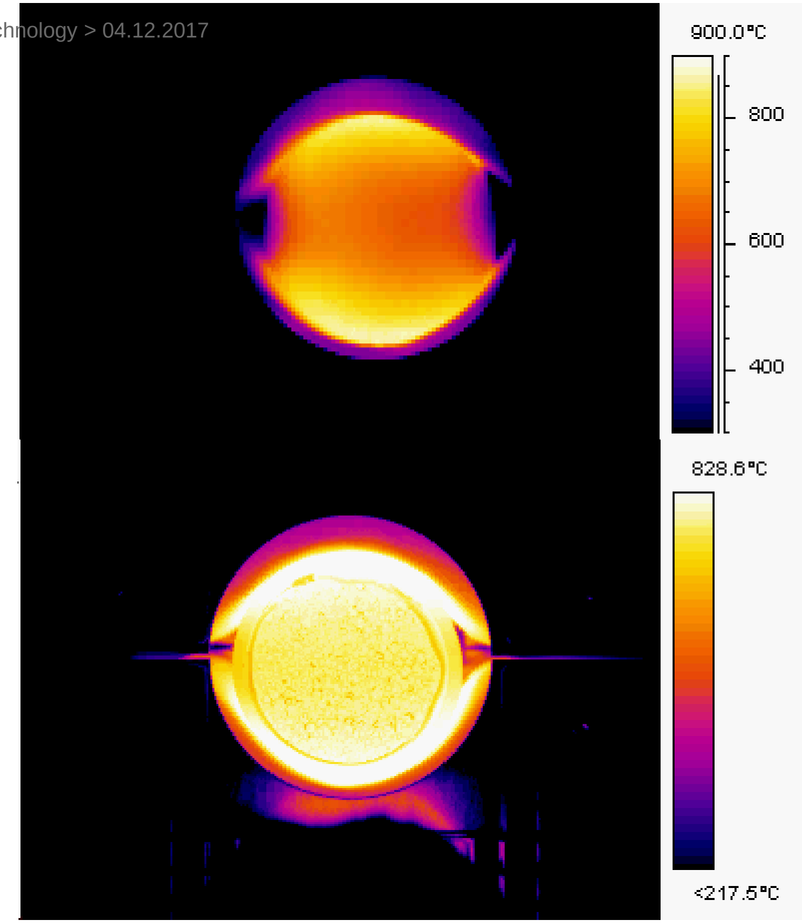
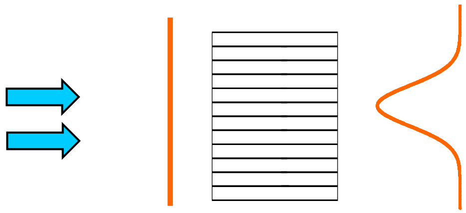
cordierite honey comb



SiC foam







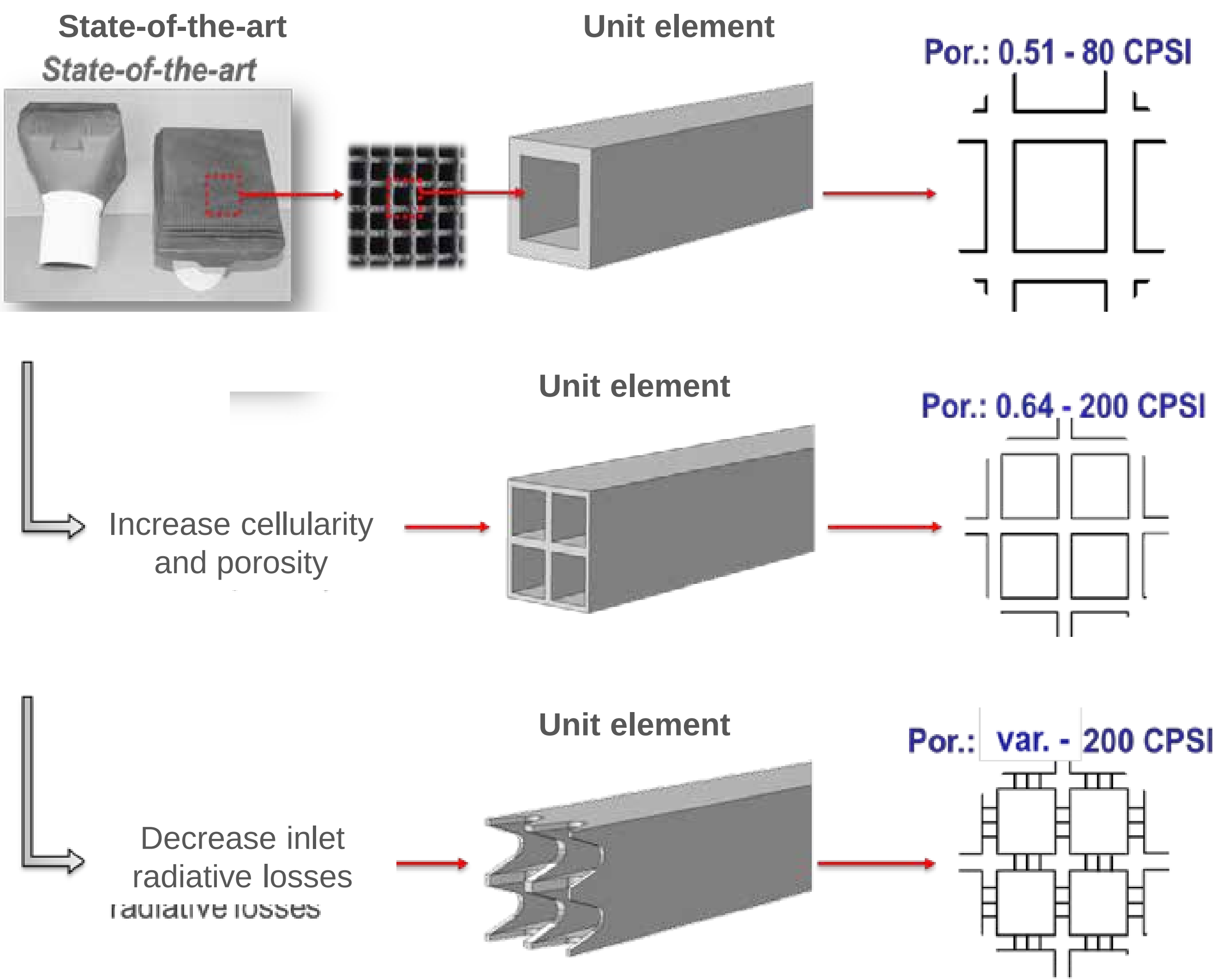
v = const.

v = 0 in hot channels

geometry/pressure loss characteristics influences flow stability

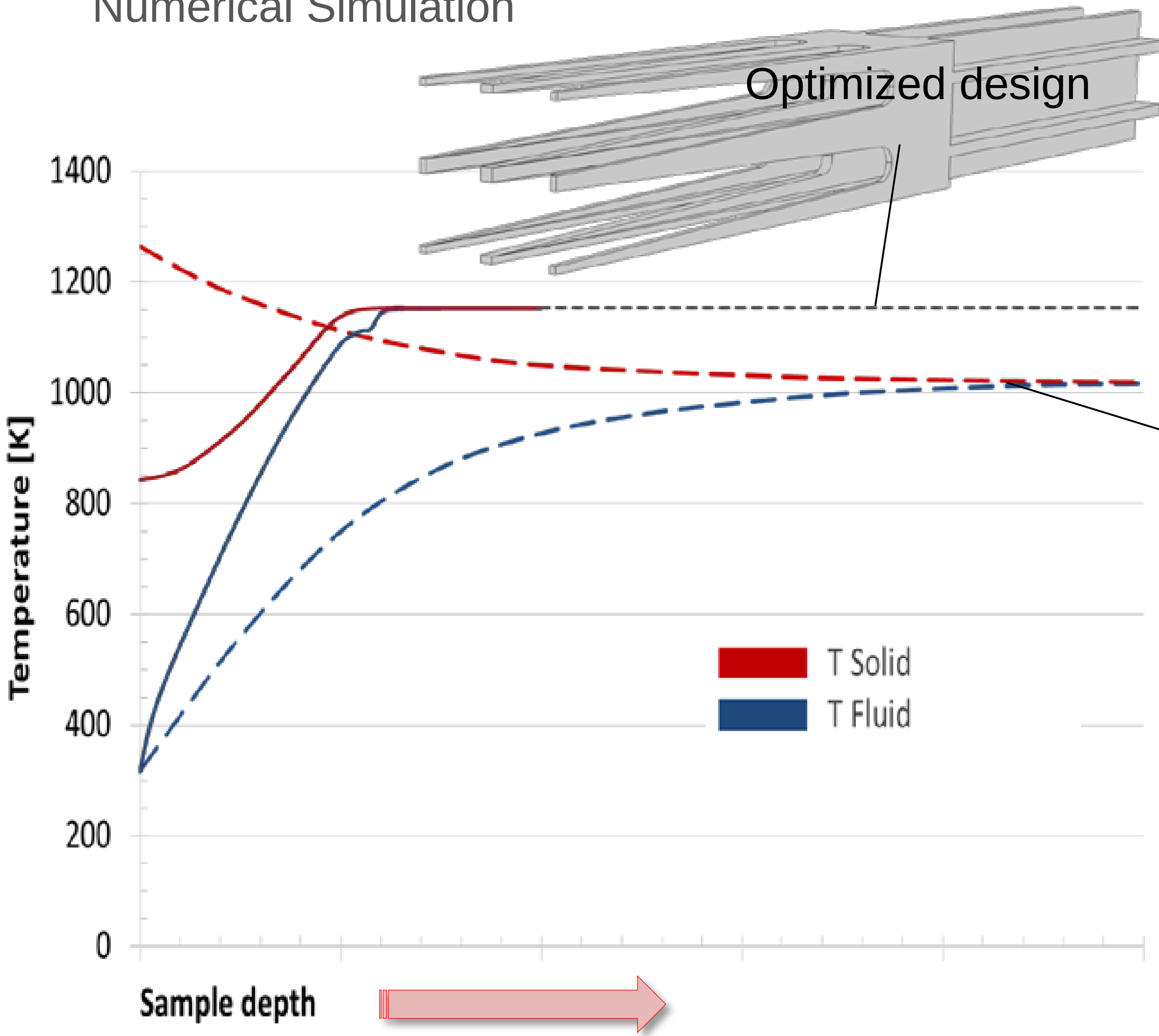
heat conductivity influences flow stability

Optimizing the Absorber Design



Optimizing the Absorber Design

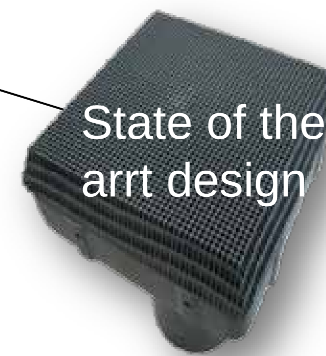
Numerical Simulation



Innovative geometry

$T_{air\text{-}out}$: 1149 K

η = 90 %



HiTRec-II

$T_{air\text{-}out}$: 1012 K

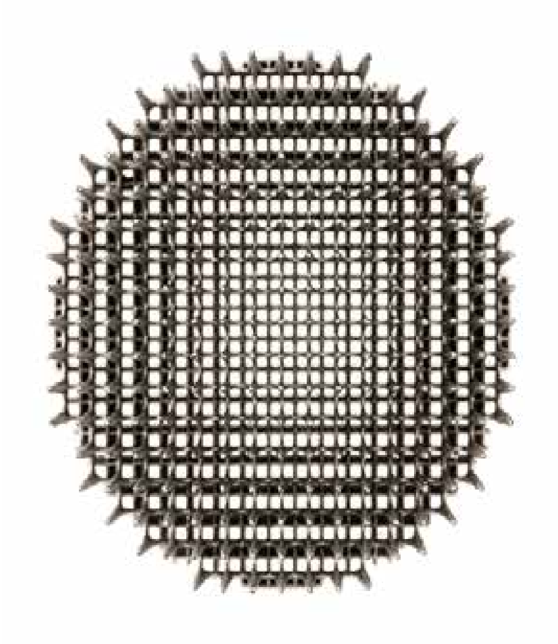
η = 72%

Prototype sample production by 3D printing

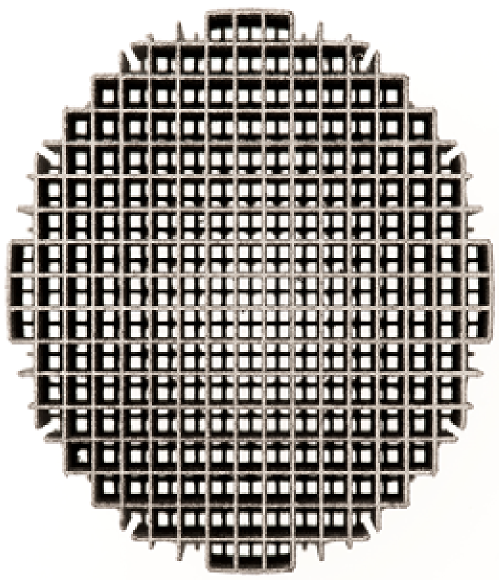
Cylindrical prototype test-sample: Ti6Al4V 3:1 scaled up geometry

Front view

Top view



Bottom view



Fraunhofer IFAM

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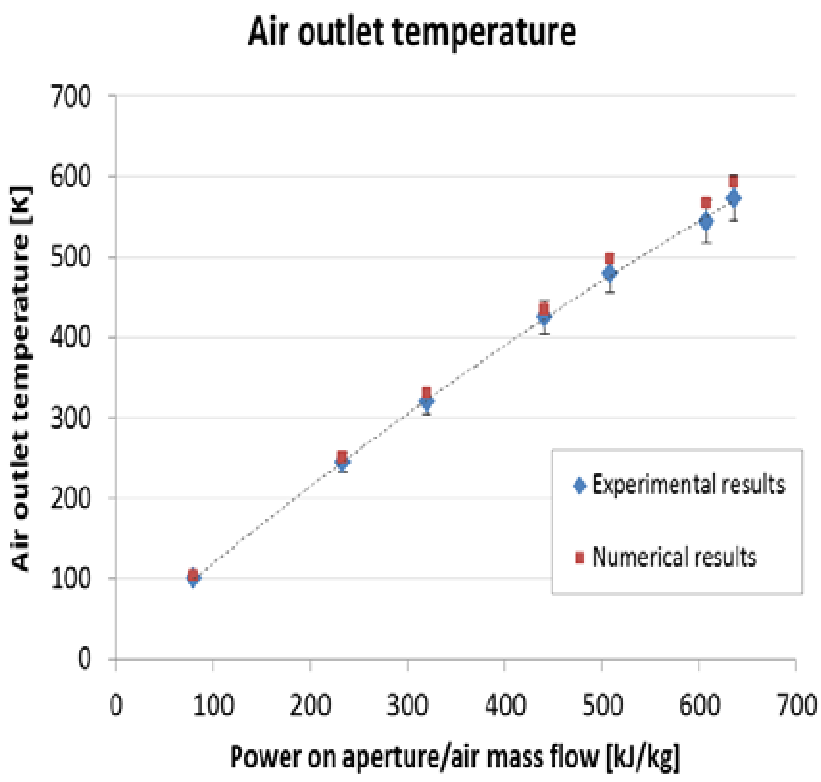
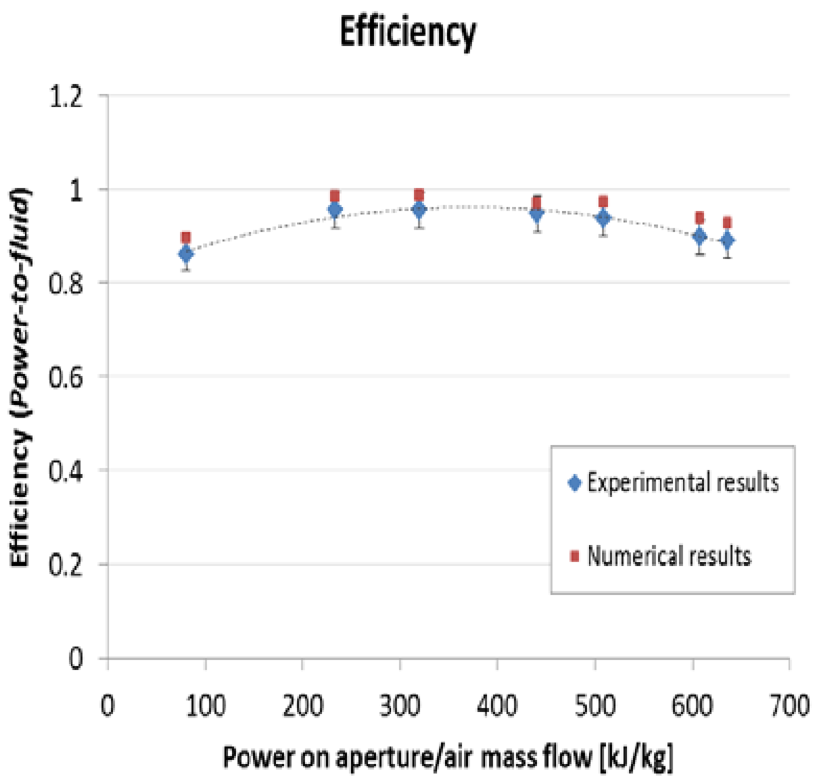
Experimental Validation of Prototype

Thermal efficiency evaluation à 20 kW solar simulator





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    - Shape Accuracy of Solar Concentrators
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    - Molten salt in parabolic troughs

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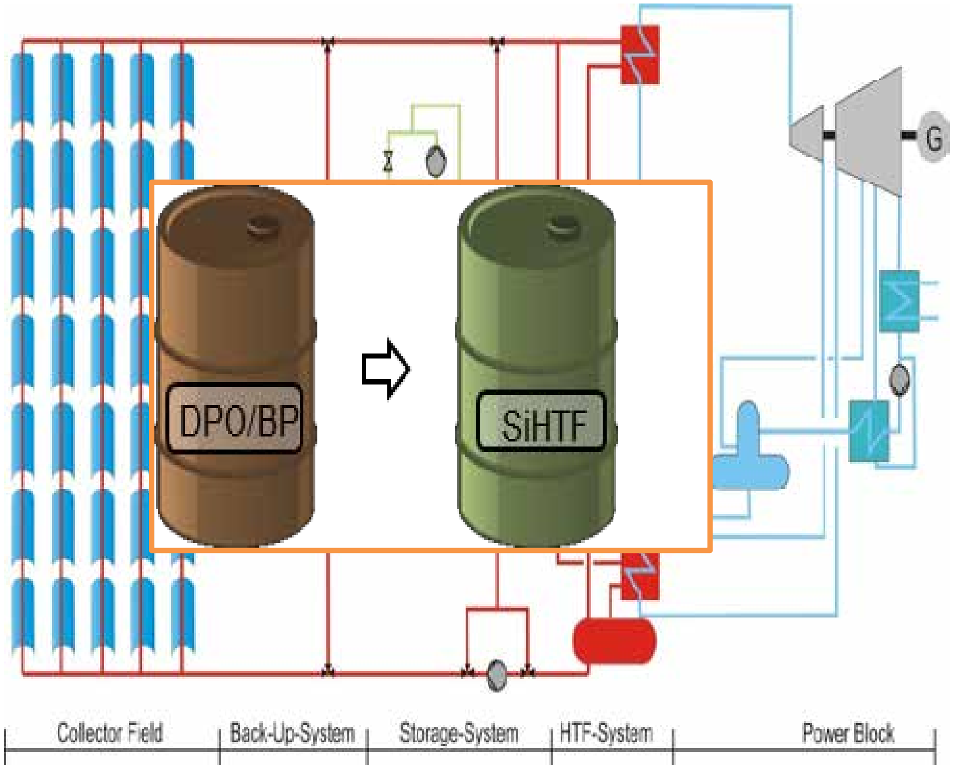
Advanced Silicon Oil in Parabolic Troughs

ü **Environmental Safety**

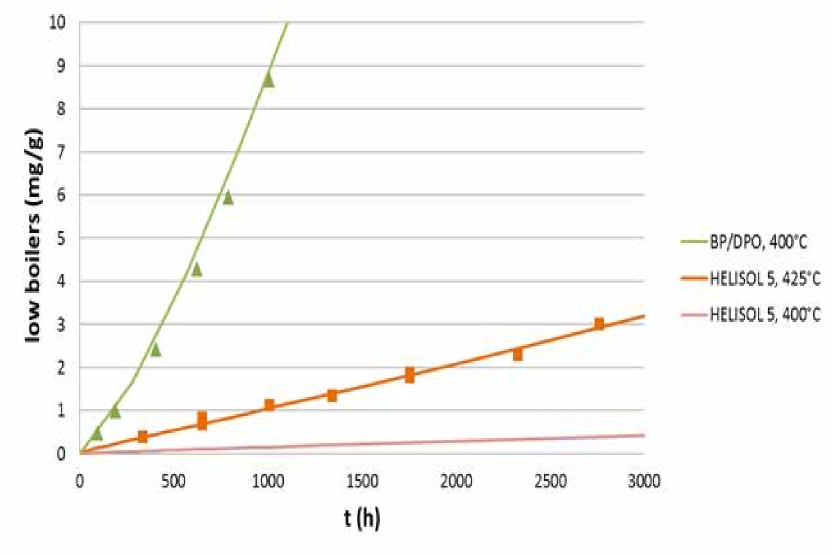
ü **Capacity / Performance**

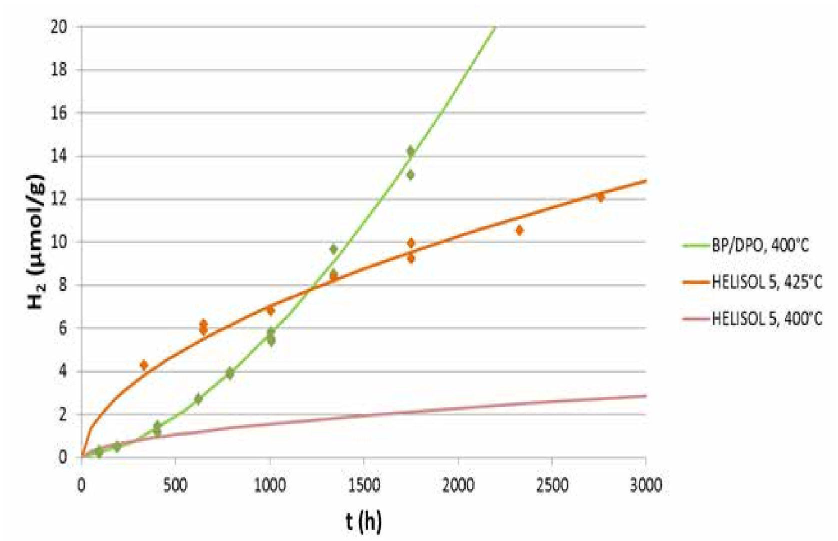
- *low pour point (-55°C) reduces auxiliary consumption for freeze protection*
- *slower degradation at 425°C in comparison to DPO/BP at only 400°C*
- *425°C field outlet temperature increases conversion efficiency of Rankine cycle and allows for smaller heat storage systems*



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)

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Advanced Silicon Oil in Parabolic Troughs

Heat transfer fluid	Unit	DPO/BP	HELISOL® 5A
Nominal solar field temperature	°C	393	430
Gross power block efficiency (wet cooling)	%	39.0	40.5
Gross power block efficiency (ACC)	%	37.7	39.2
Nominal specific solar field parasitics	W/m^2	8	6.4
Specific investment solar field	$€/m^2$	235	235
Specific investment storage	€/kWh	40	33
Specific HTF cost (identical)	€/kg	4	4
Annual HTF replacement rate (identical)	%	2	2
Mean volumetric heat capacity	$kJ/(m^3K)$	1871	1397

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

SITEF Project
2016-2017

by courtesy of CIEMAT

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)

German Aerospace Center

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

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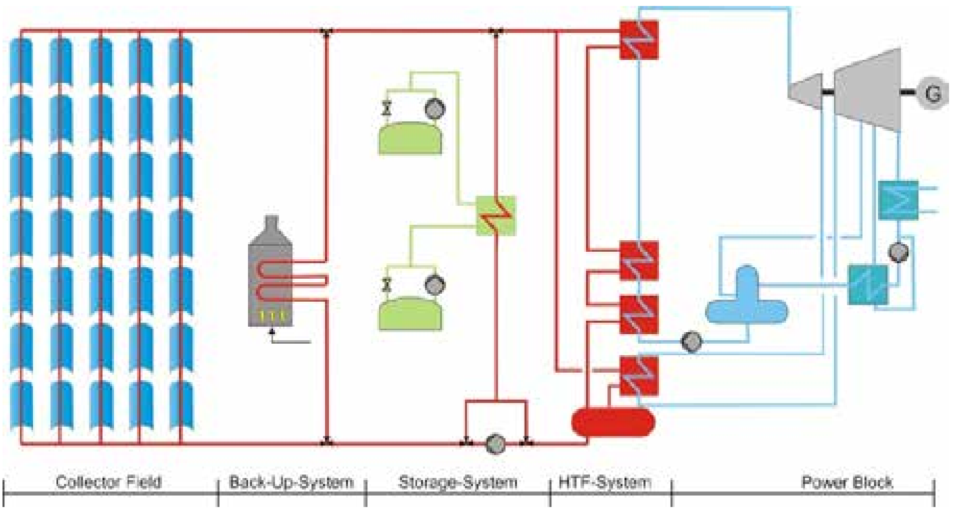
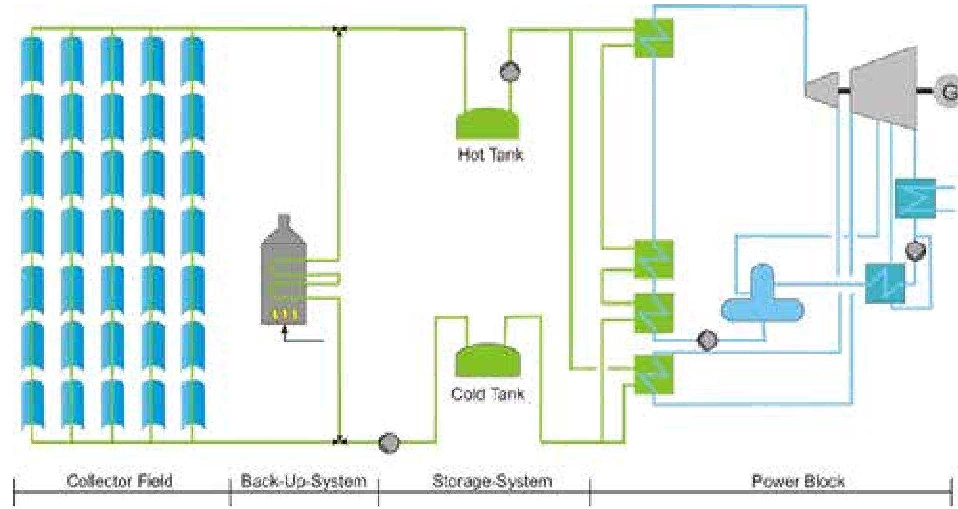
Molten Salt in Parabolic Trough Power Plants



Thermal oil (TO) based plant



Molten salt (MS) based plant

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

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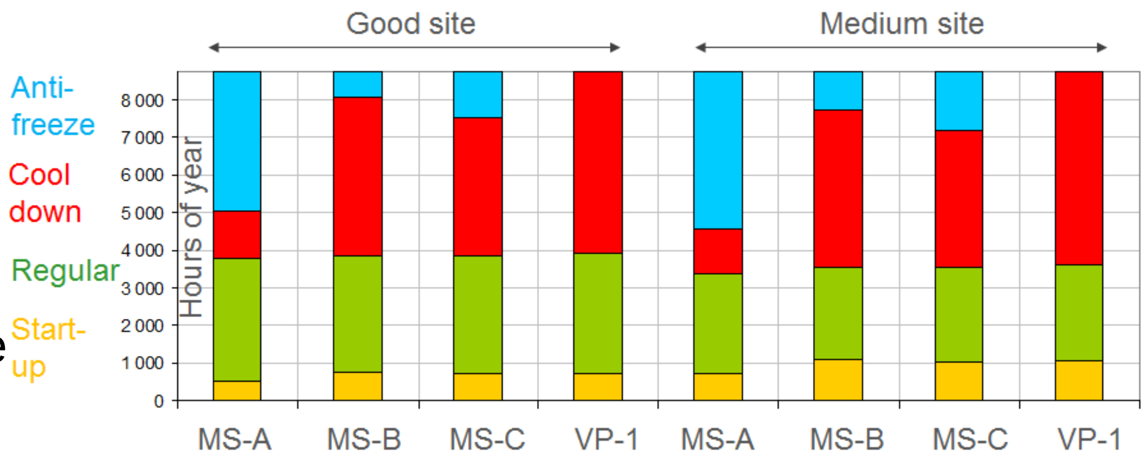
Parabolic Trough Night operation /w molten salt

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

Salt Mixtures	Decomp. Temperature	Freezing Temperature
MS-A NaK-NO_3 (Solar Salt)	>550°C	238°C @ 60/40 Mixture
MS-B NaKCa-NO_3	<500°C	~150°C
MS-C NaKLi-NO_3	~530°C	~140°C

- 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.



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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

Control Room

Once-Through Steam Generating System

W/S-Cycle

Wind Fence

Solar Field Site

Thermal Energy Storage

Drainage Tank with permanent Melting Unit

HelioTrough loop will be installed

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

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

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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