Everything You Always Wanted to Know About CSP *
*But Were Afraid to Ask

Robert Pitz-Paal

Outline

1. Characteristics of CSP

2. Market und Cost Development

3. Benefits for a mix of PV und CSP

4. Scientific Challenges in CSP Development
   - Shape Accuracy of Solar Concentrators
   - Controlling the Solar Flux Distribution
   - Stable and efficient Volumetric Receivers

5. Conclusions

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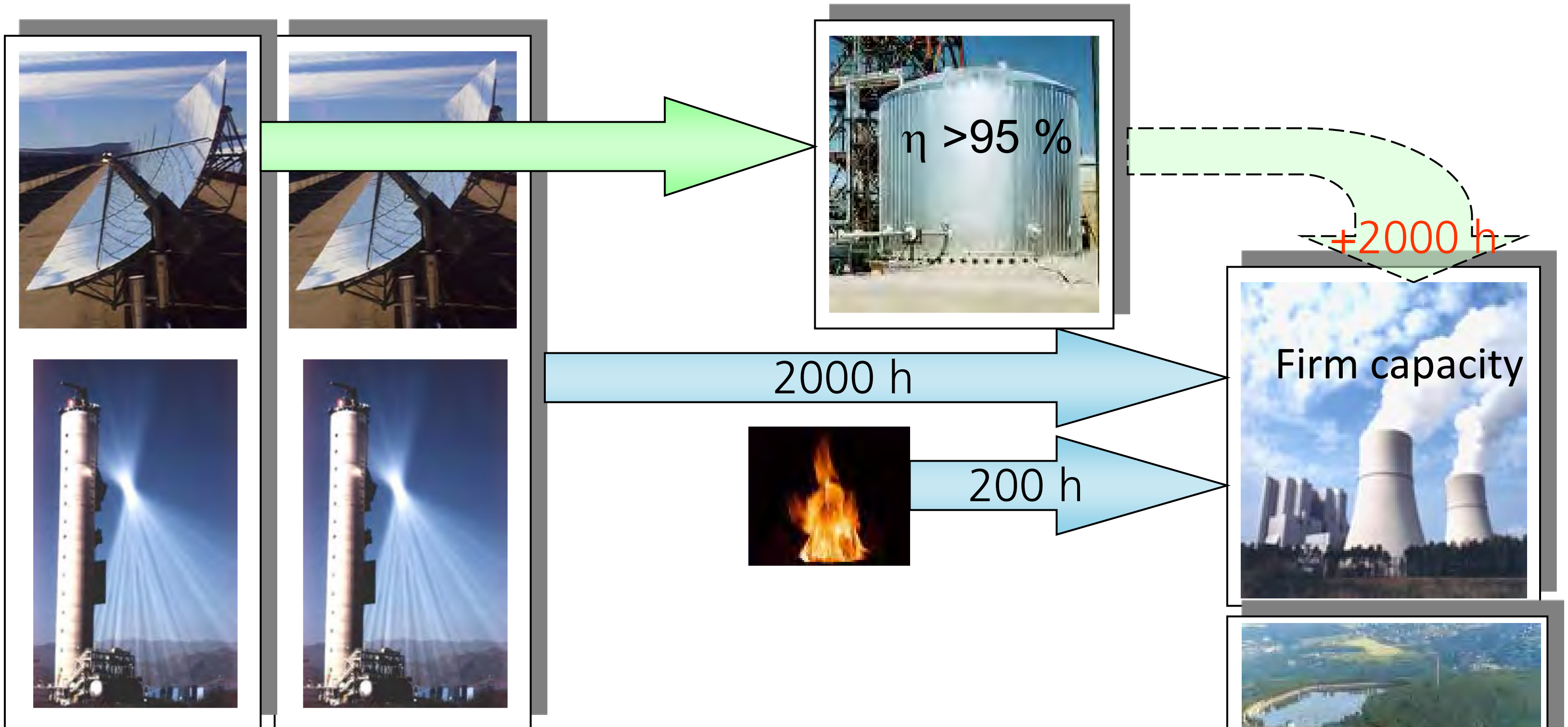
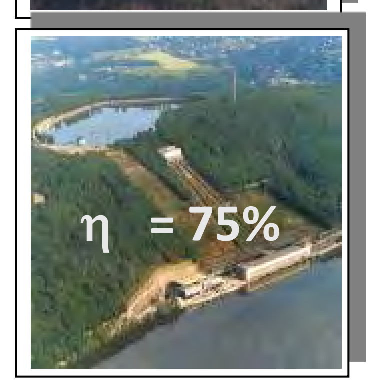
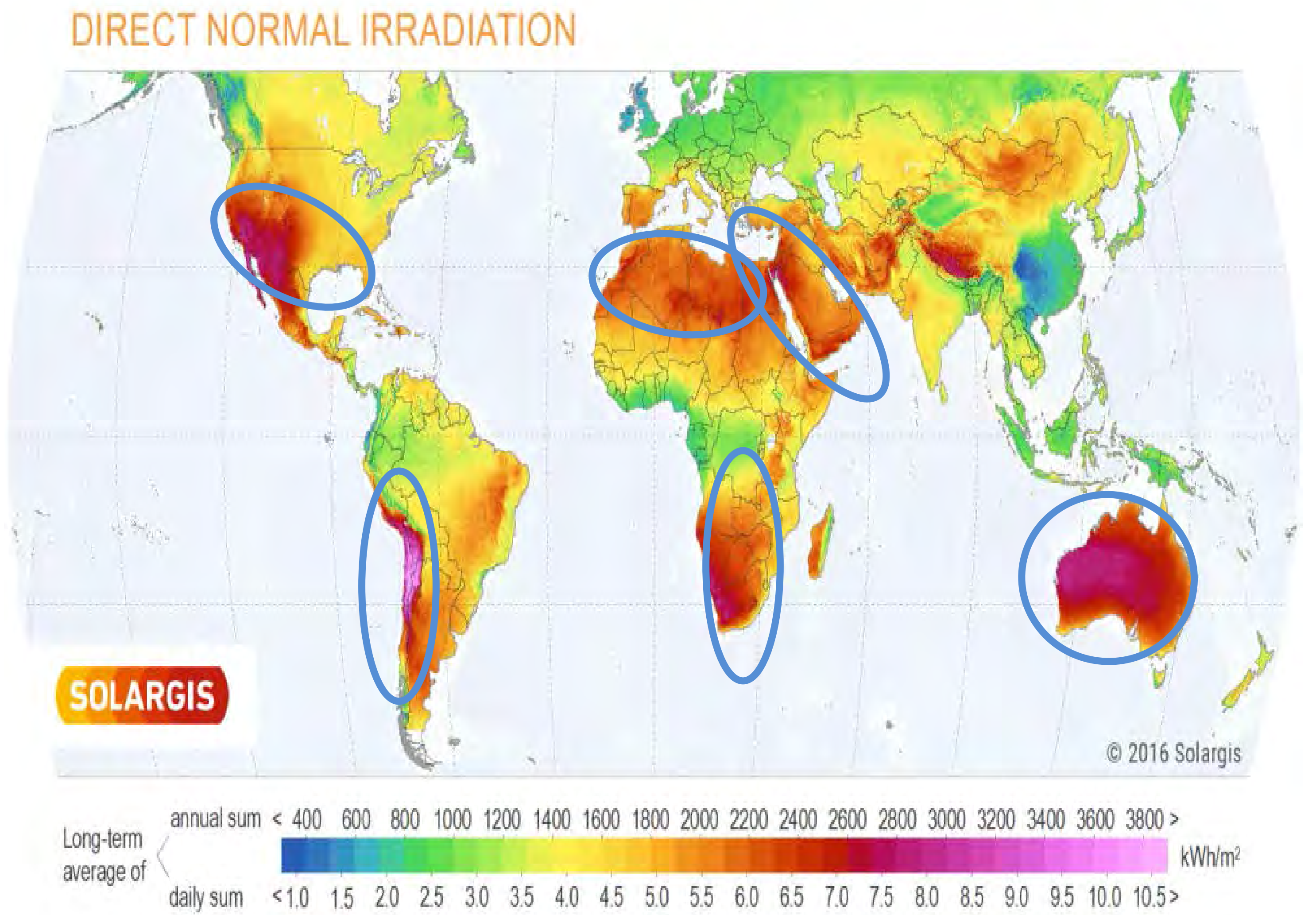
Thermal Storage vs. Electric Storage





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



DLR

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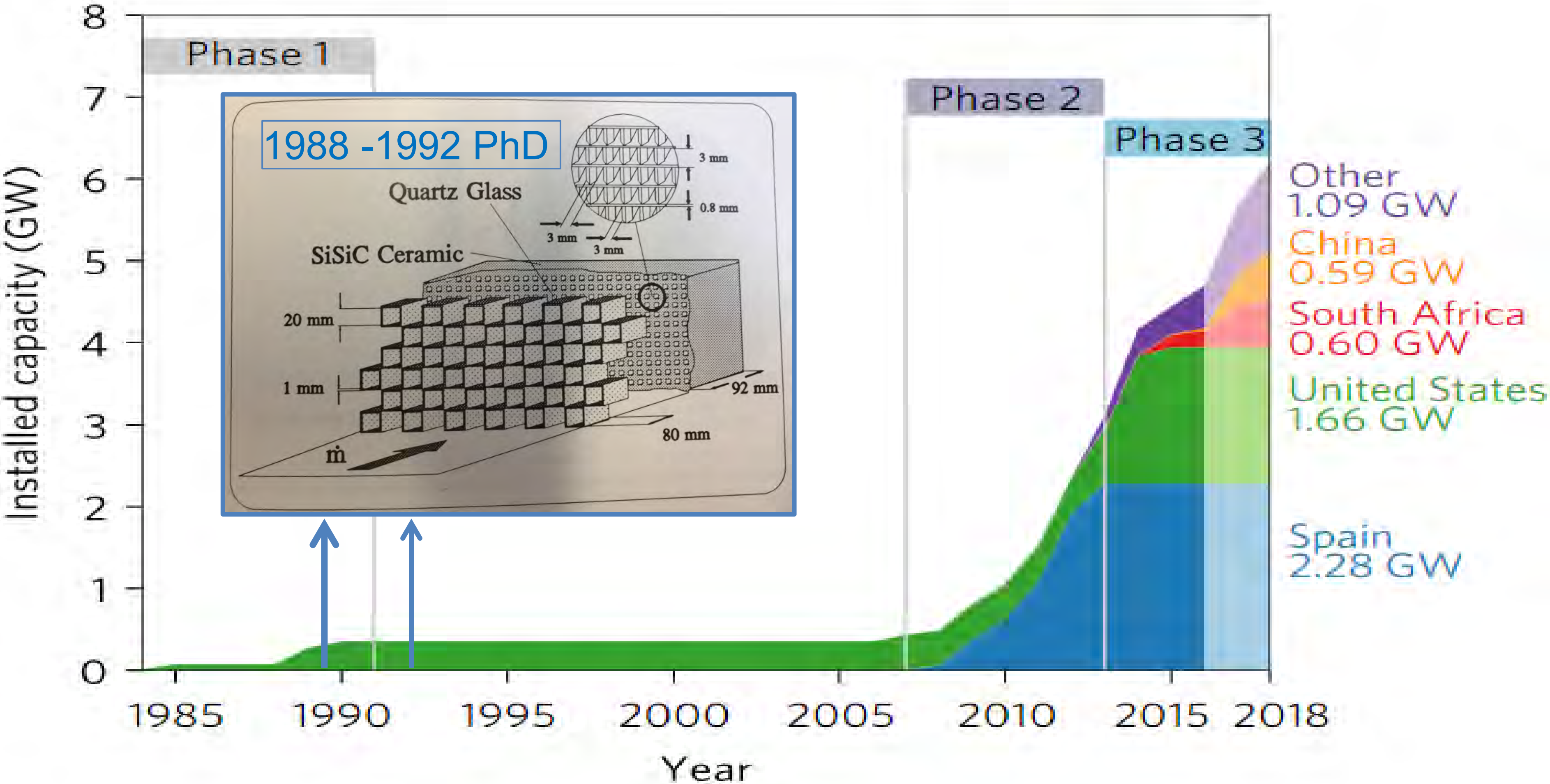
Global expansion of CSP in three phases



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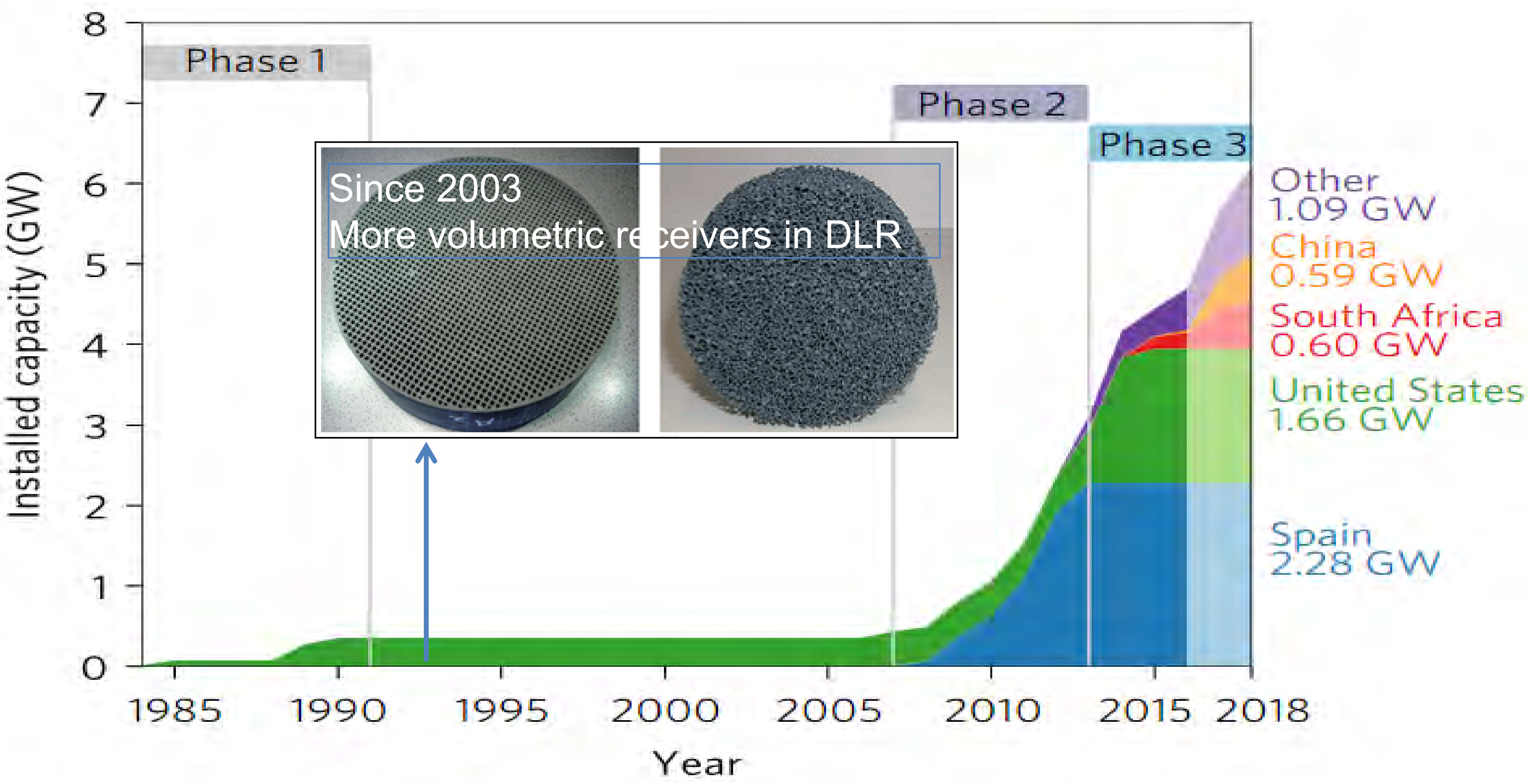
Global expansion of CSP in three phases



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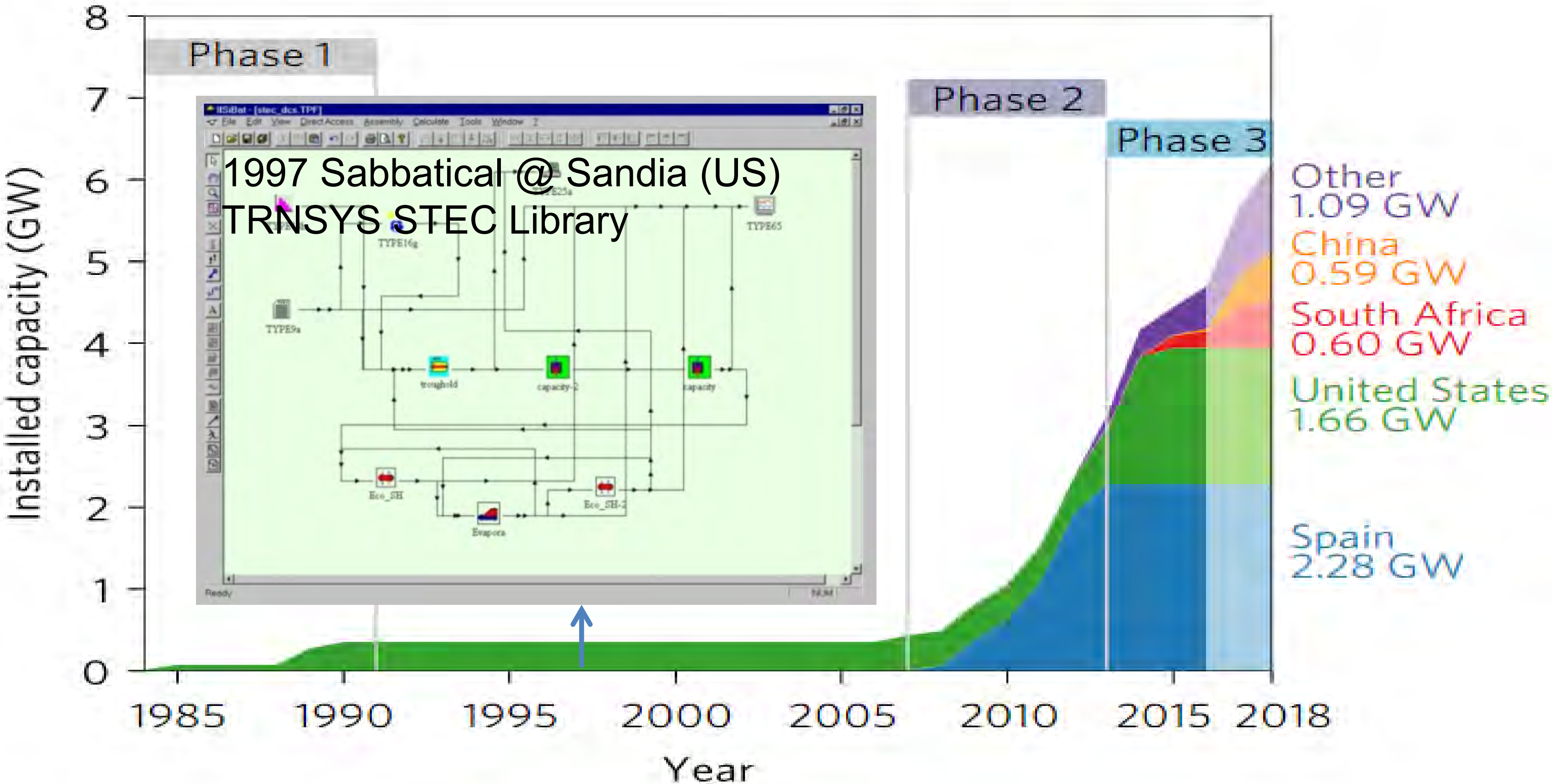

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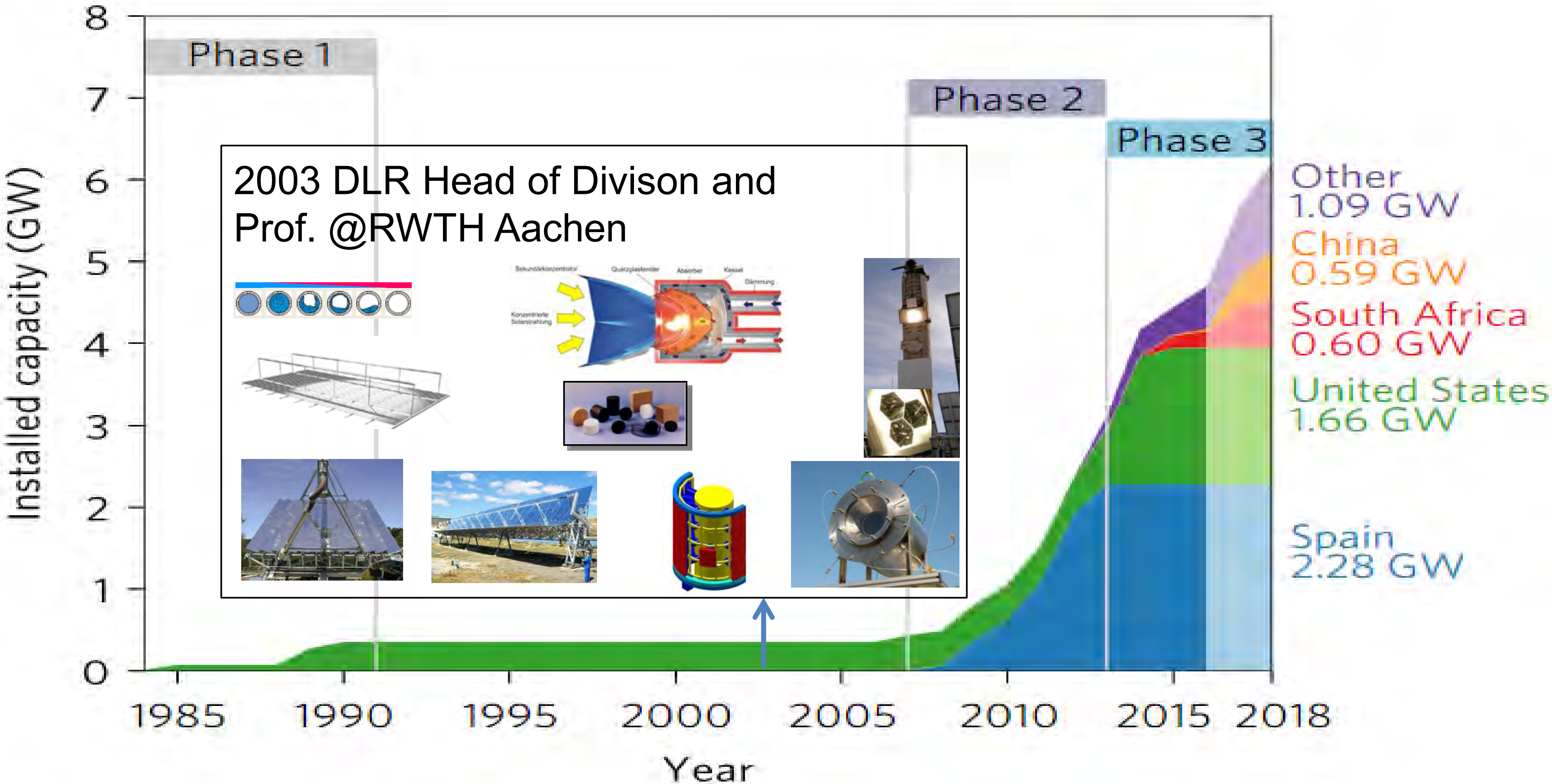

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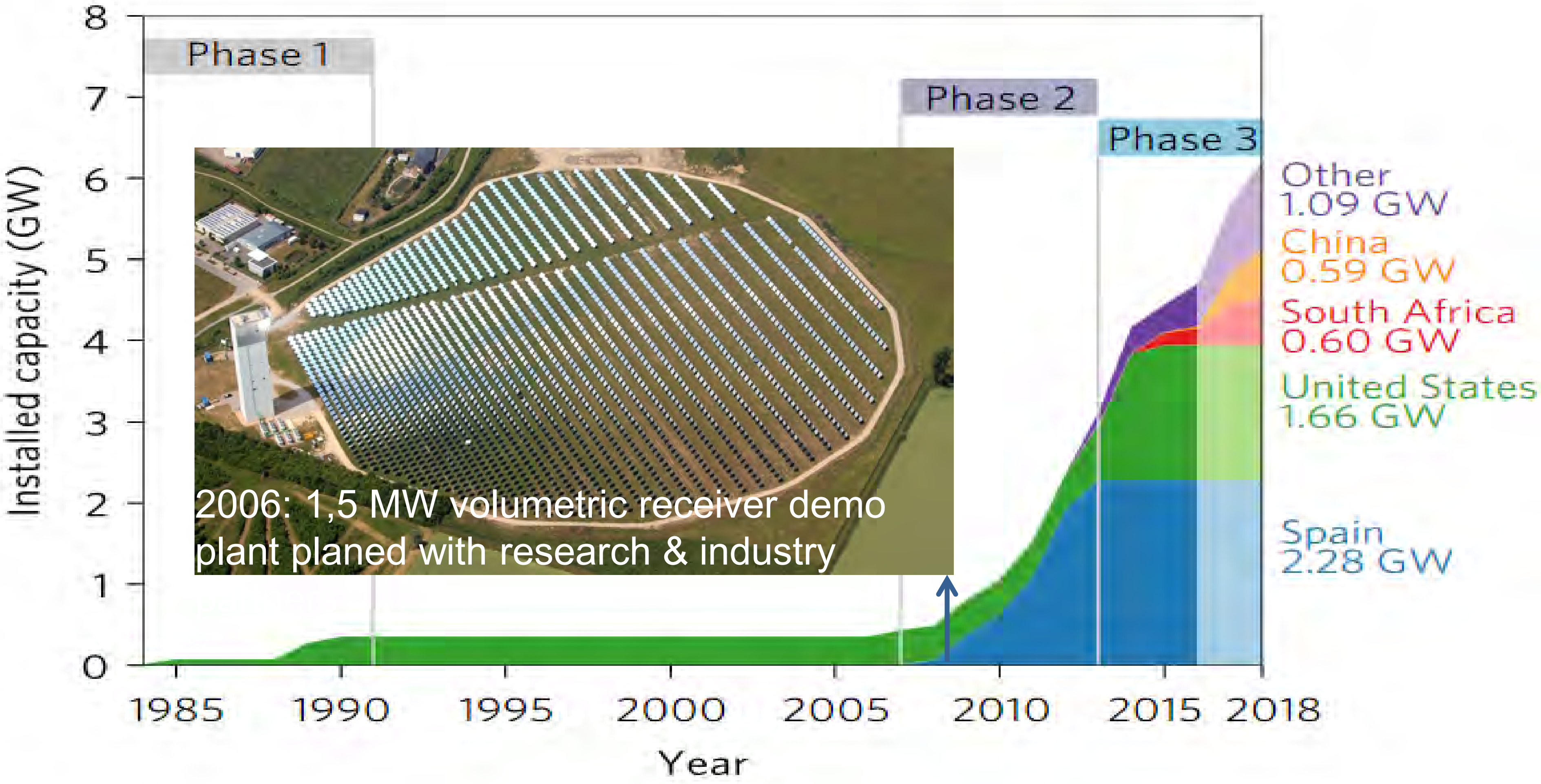

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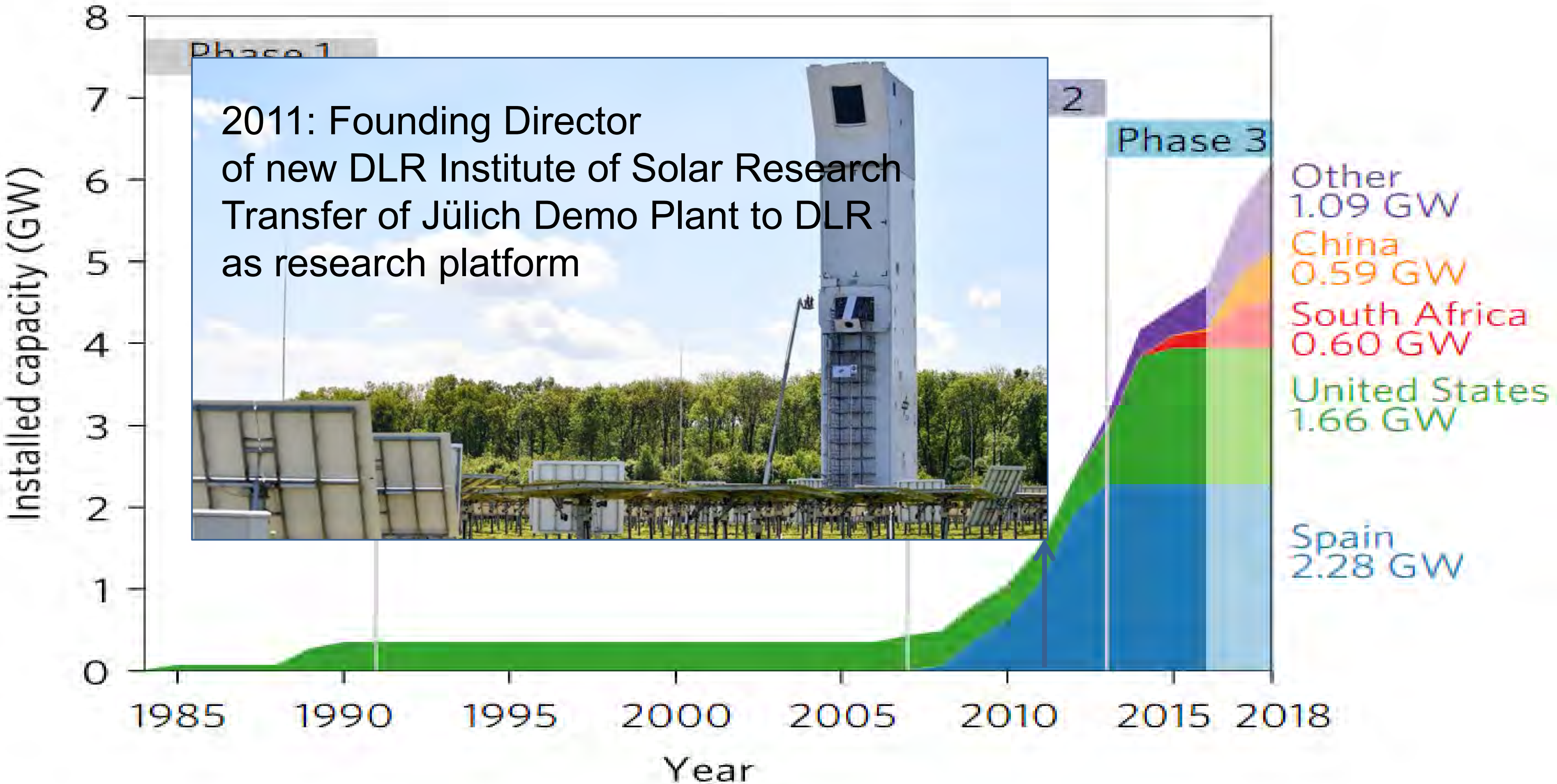
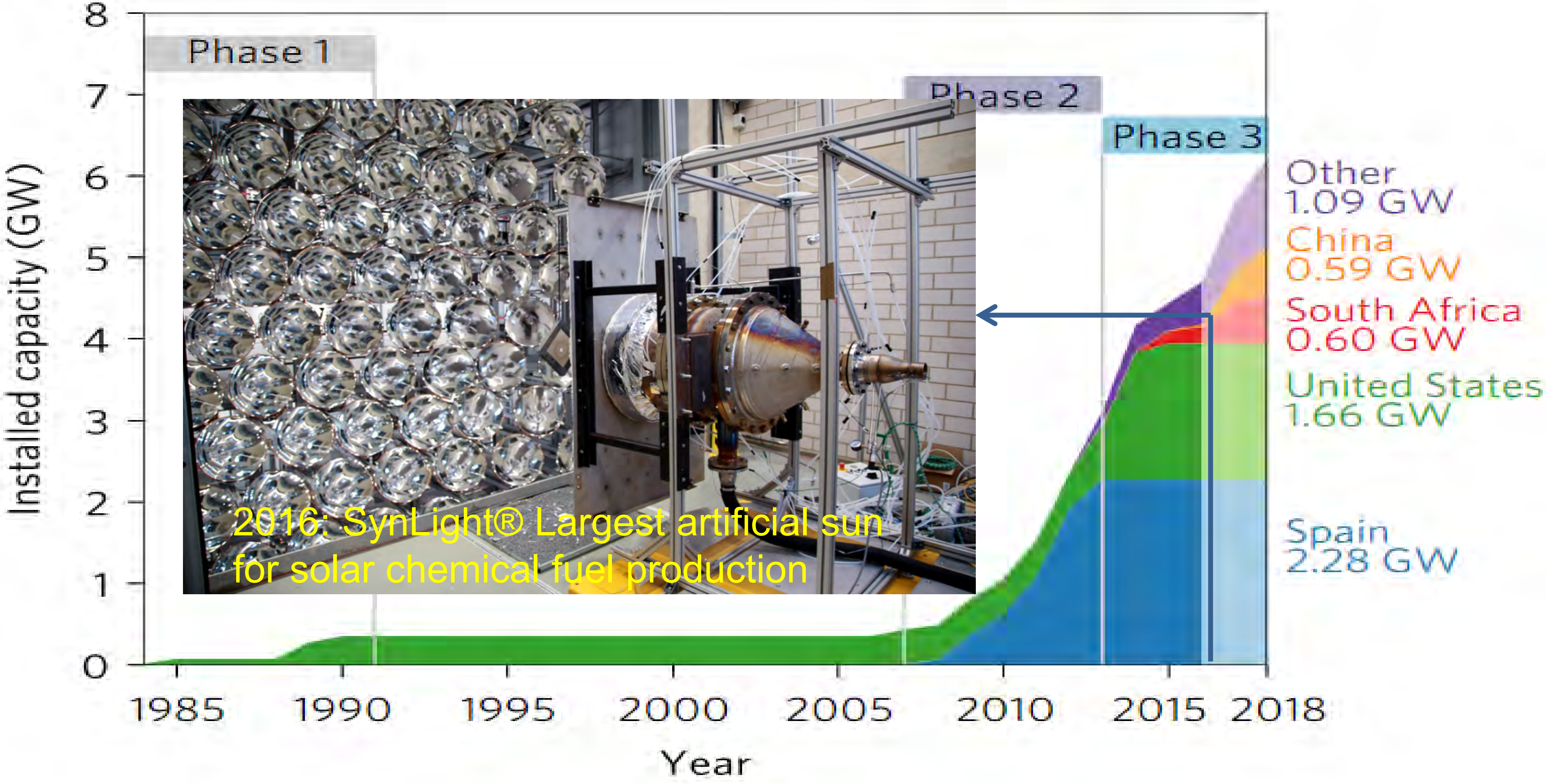


2011: Founding Director
of new DLR Institute of Solar Research
Transfer of Jülich Demo Plant to DLR
as research platform

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

Global expansion of CSP in three phases



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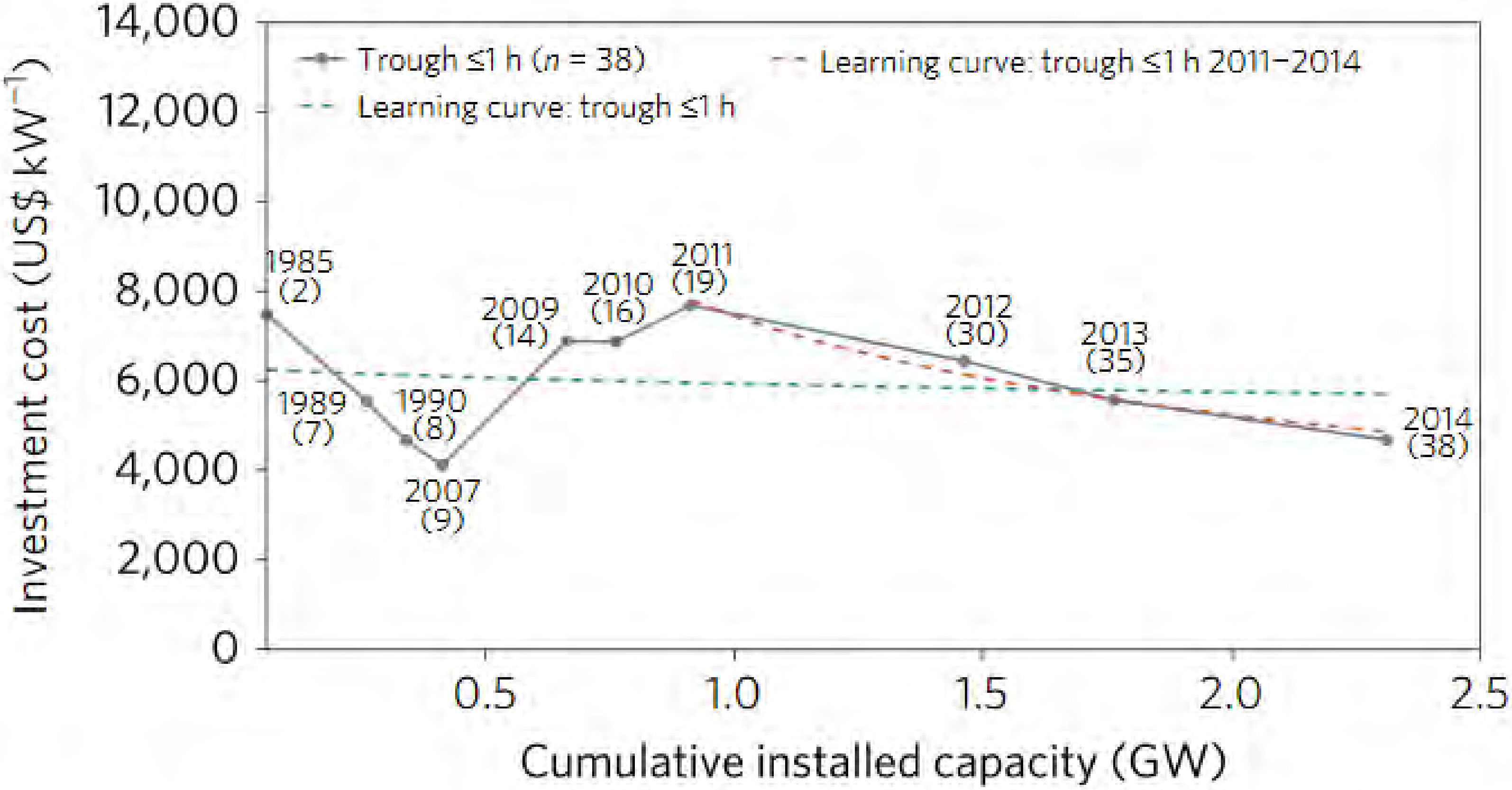
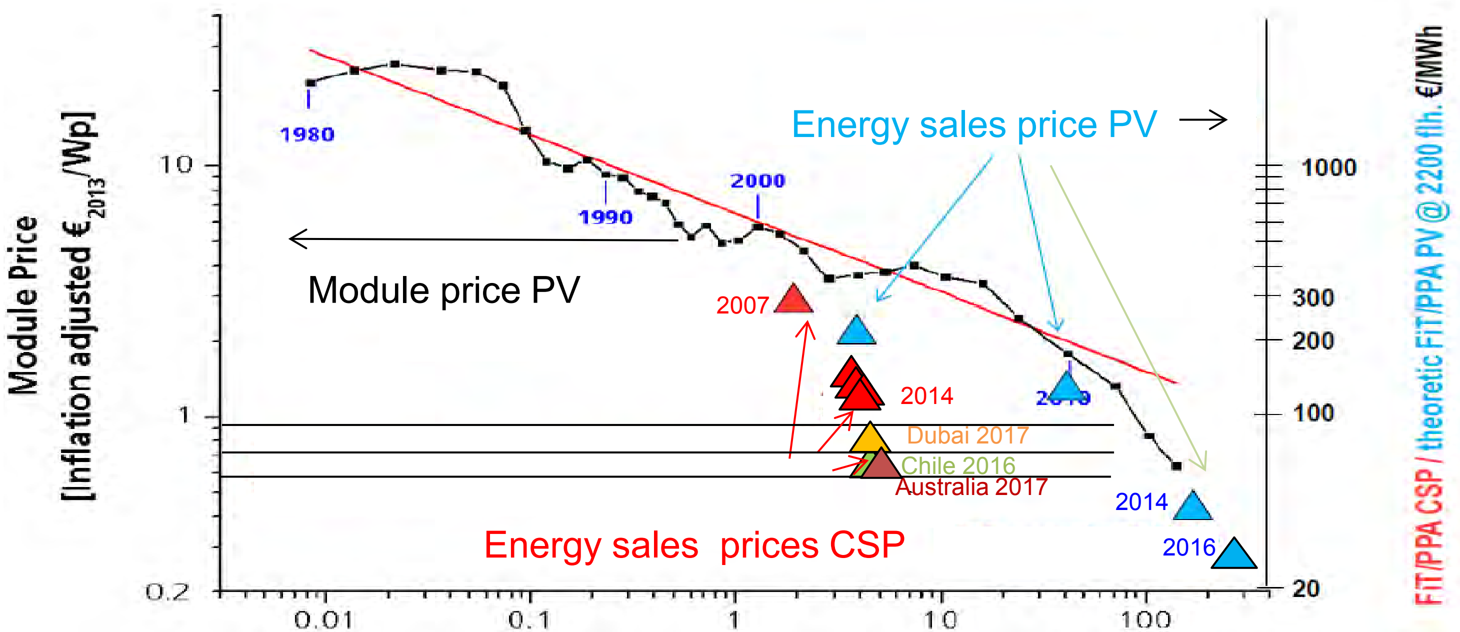
Cost reduction over last 5 years at a learning rate of > 25%



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 capacty



Source: modified, based on Navigant Consulting, EuPD, IHS, pvXchange Graph; PSE AG 2014, see also ISE 2014 S(3)/p.40

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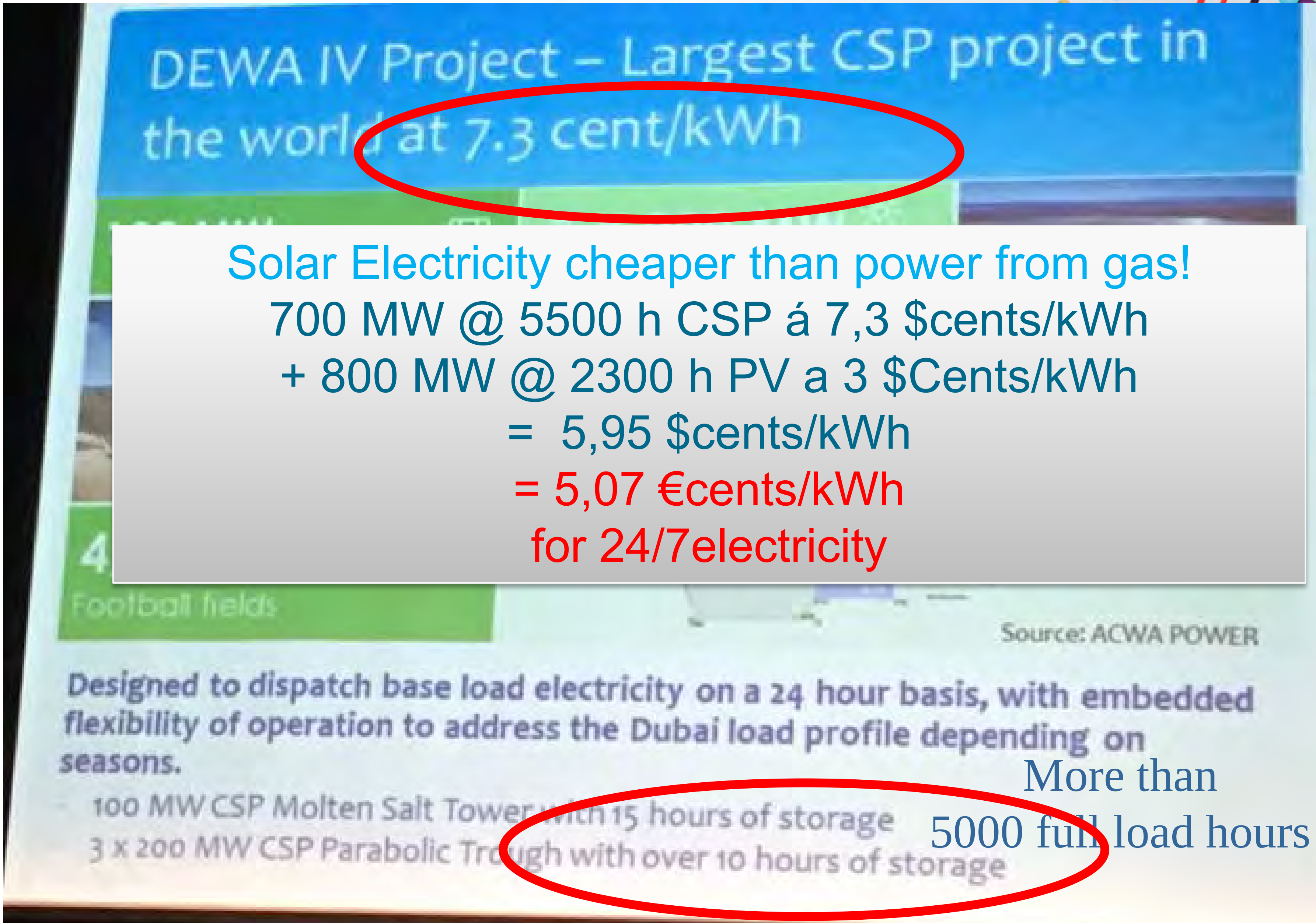

Solar Electricity cheaper than power from gas!

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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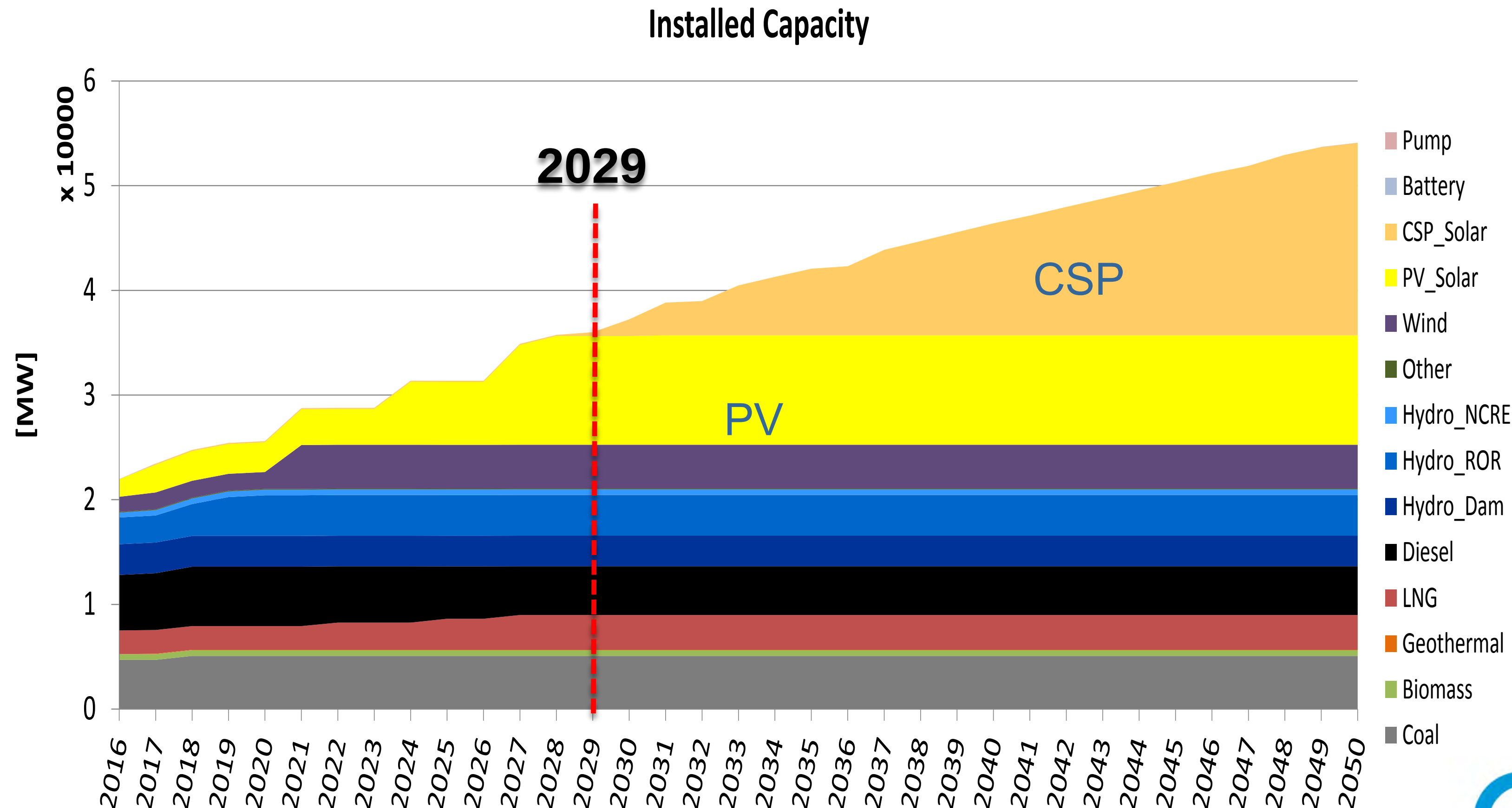
Chile Scenario Results – Expansion Model Scenario 1

	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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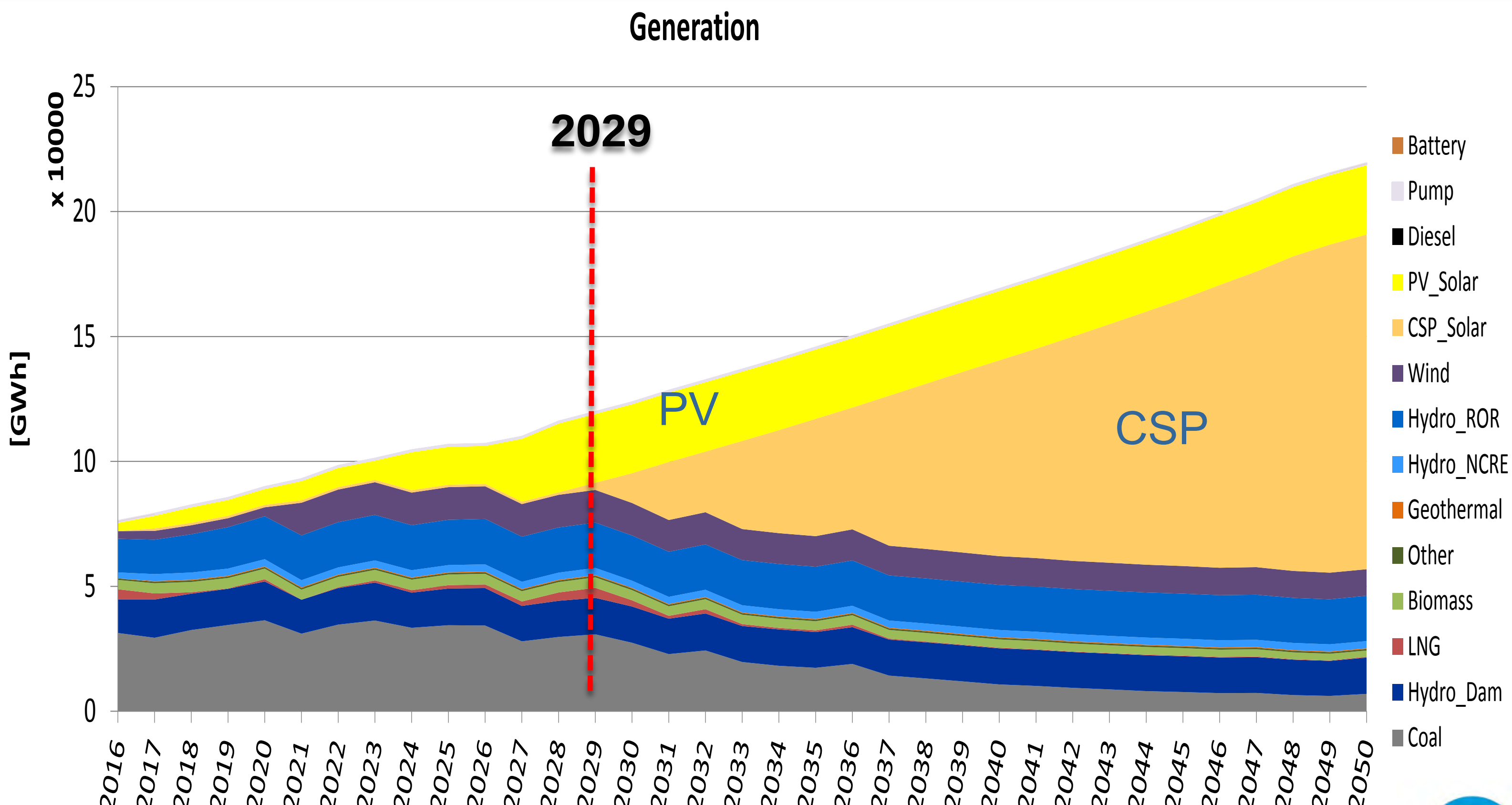
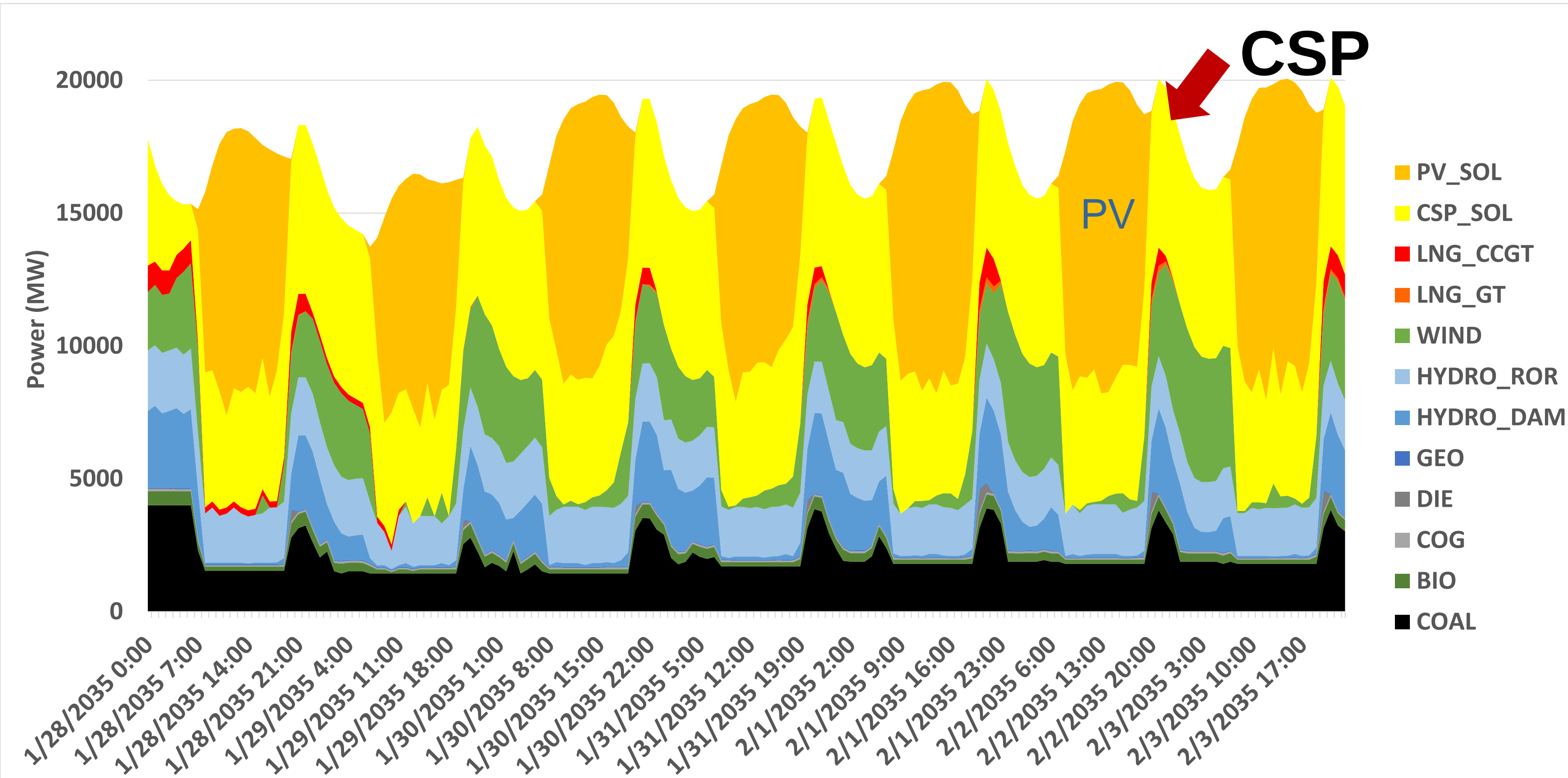


Chile Szenario results: Short Term Simulation

2035 summer week dispatch by technology



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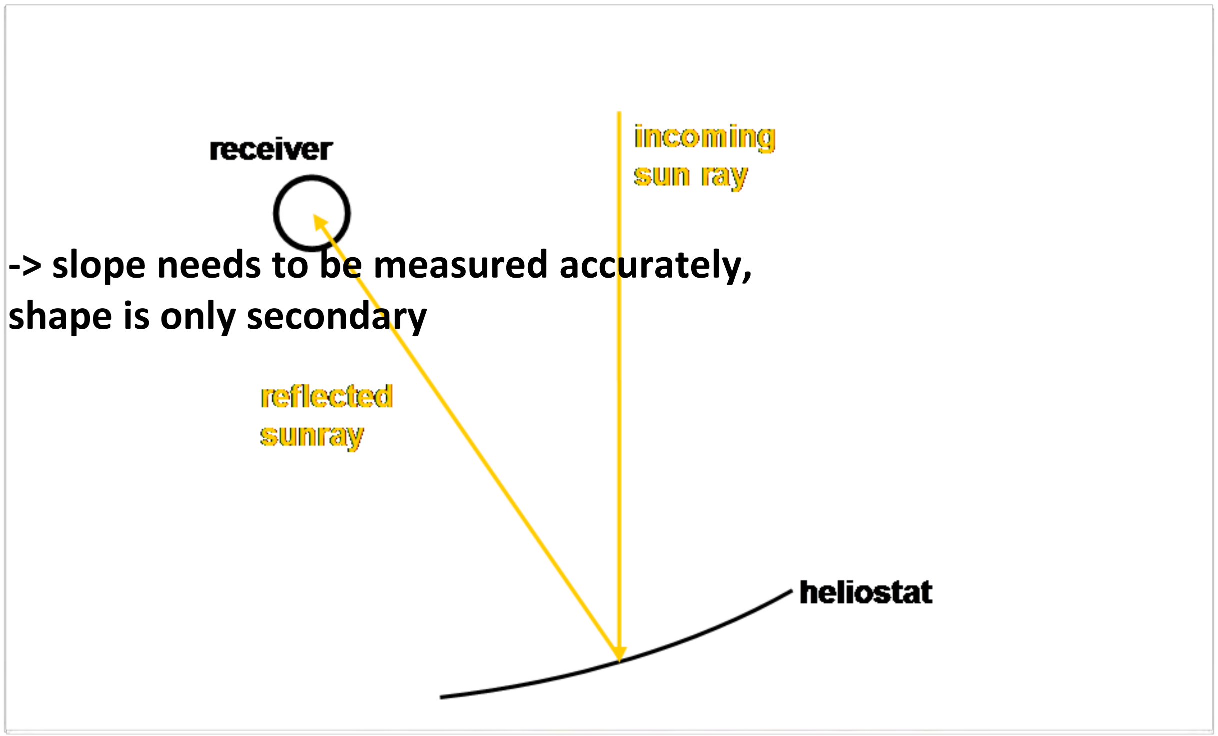
Introduction: Shape and Slope Deviations

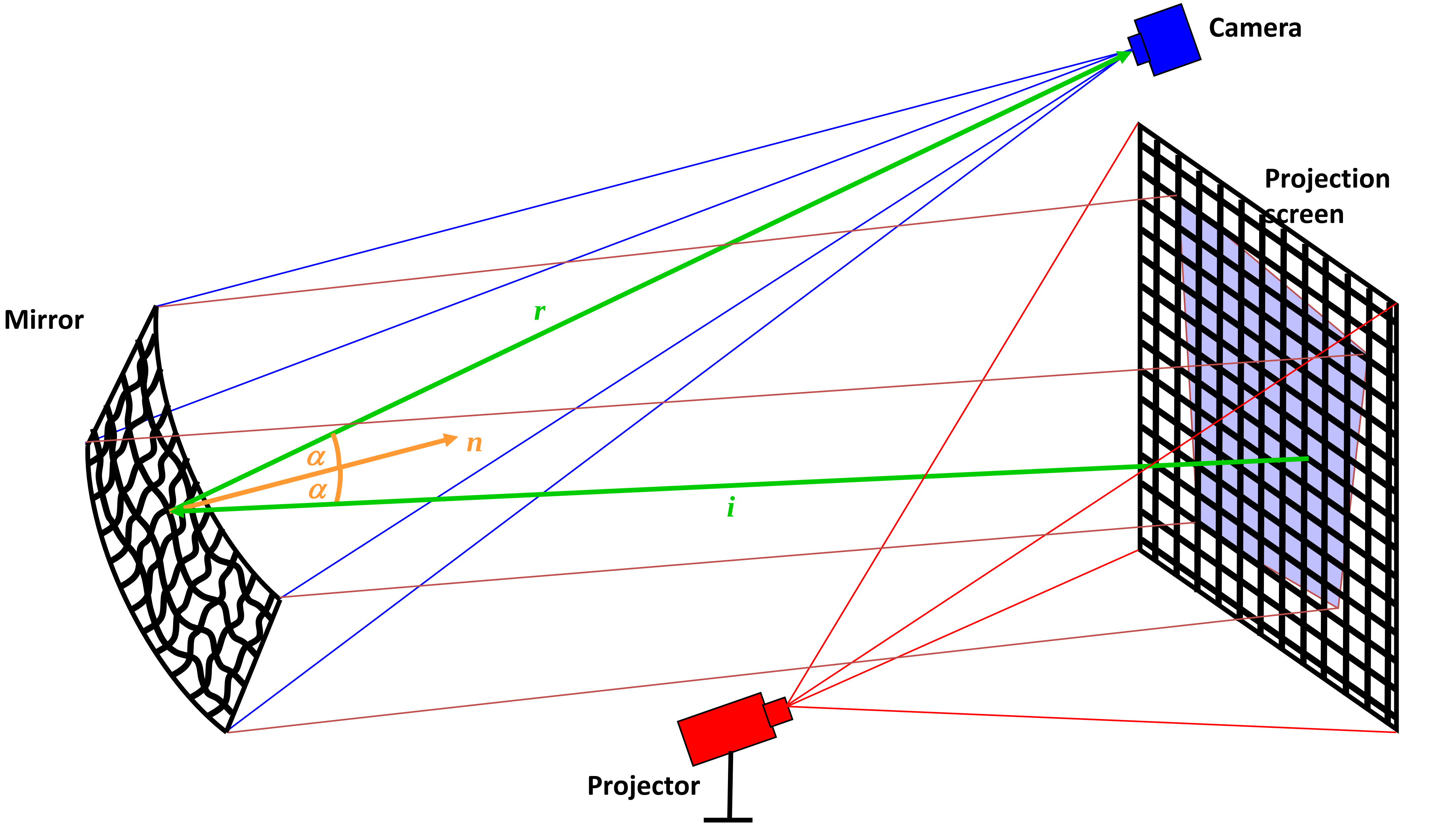
Deviations of the ideal shape of curved mirrors for CSP applications can have a significant impact on the optical efficiency and thus the performance of the power plant.

Critical measure is slope deviation, not shape deviation:

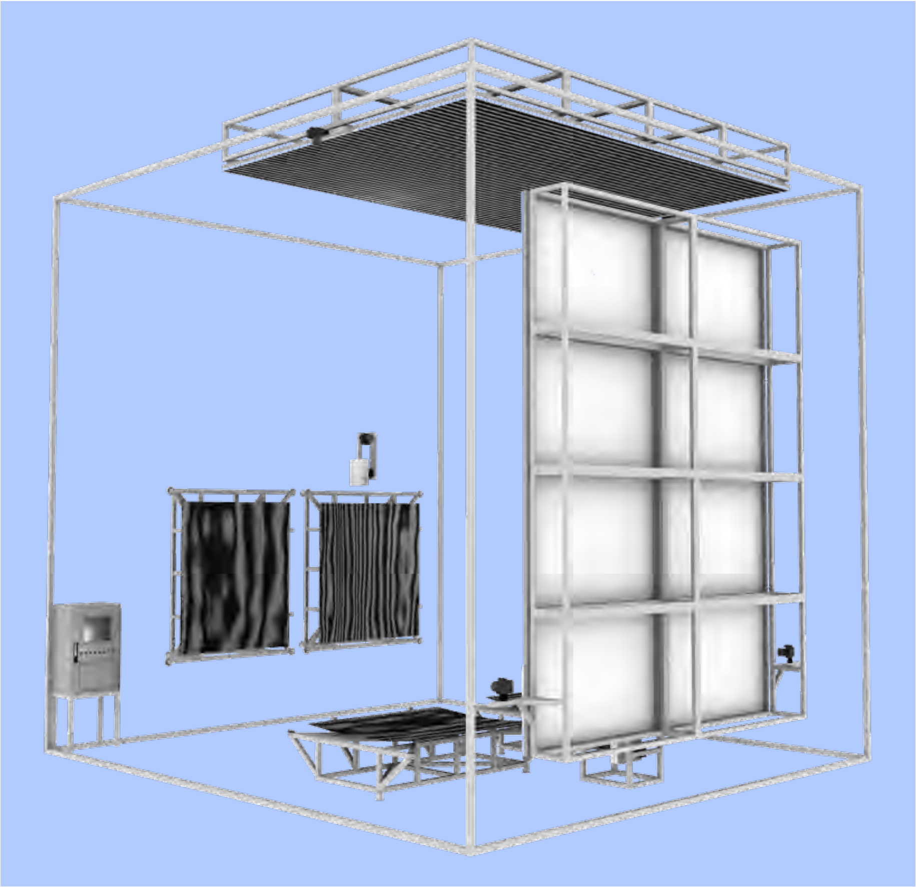


-> slope needs to be measured accurately, shape is only secondary

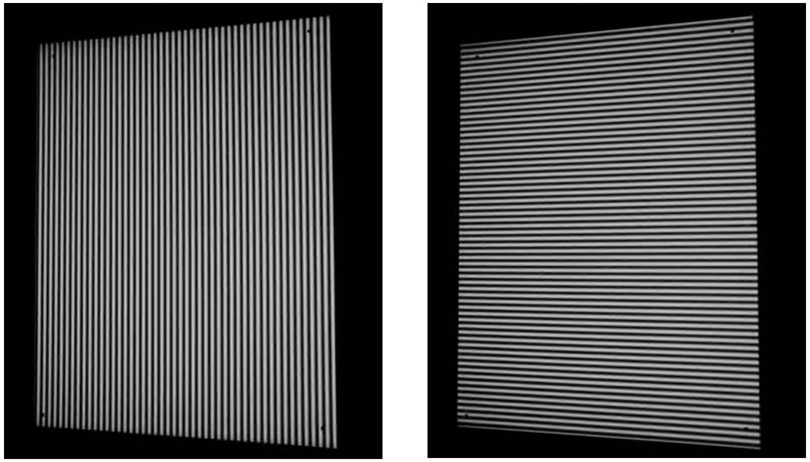
Deflectometry: Measurement Principle



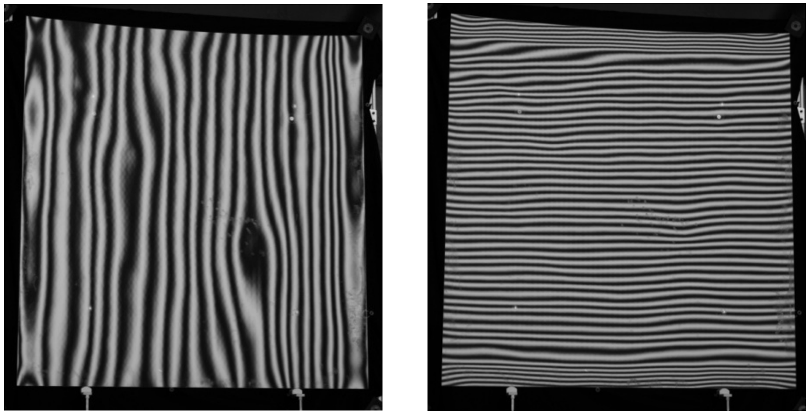
Measurement Set-Up for Individual Mirror Panels



QDec set-up for horizontal and vertical measurement

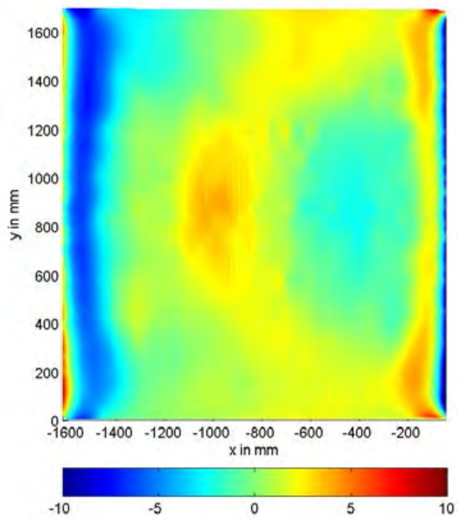


Projected horizontal and vertical stripe patterns



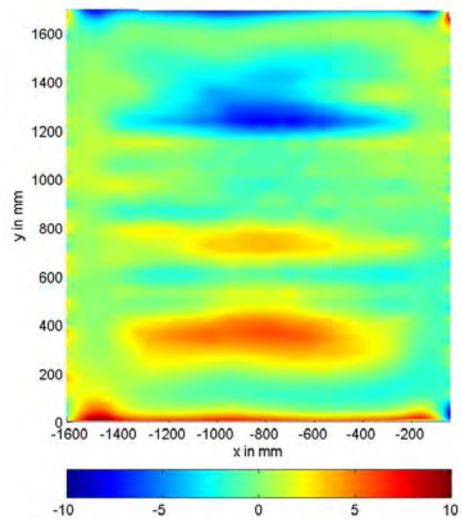
Reflected horizontal and vertical stripe patterns

Example Result for ParabolicTrough Mirror Panel



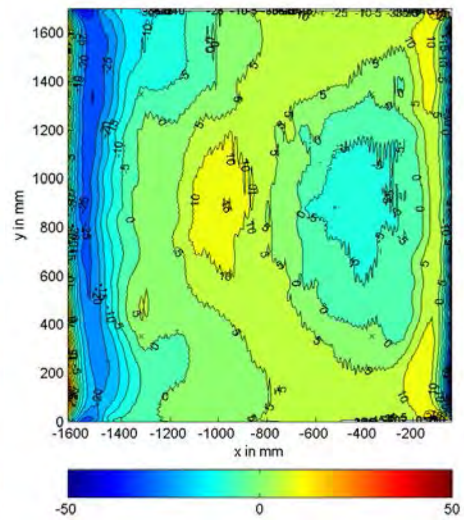
SDx = 2.5 mrad

RMS value
of slope deviation
in curved direction



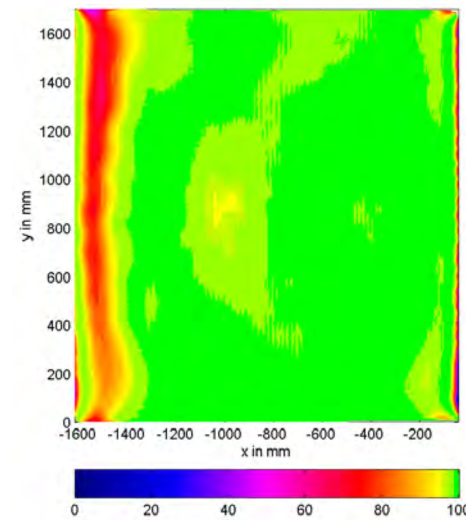
SDy = 2.2 mrad

RMS value
of slope deviation
in non-curved direction



FDx = 9.5 mm

RMS value
of focus deviation



Intercept = 96.8%

Expected intercept
considering sunshape
and additional typical
collector errors

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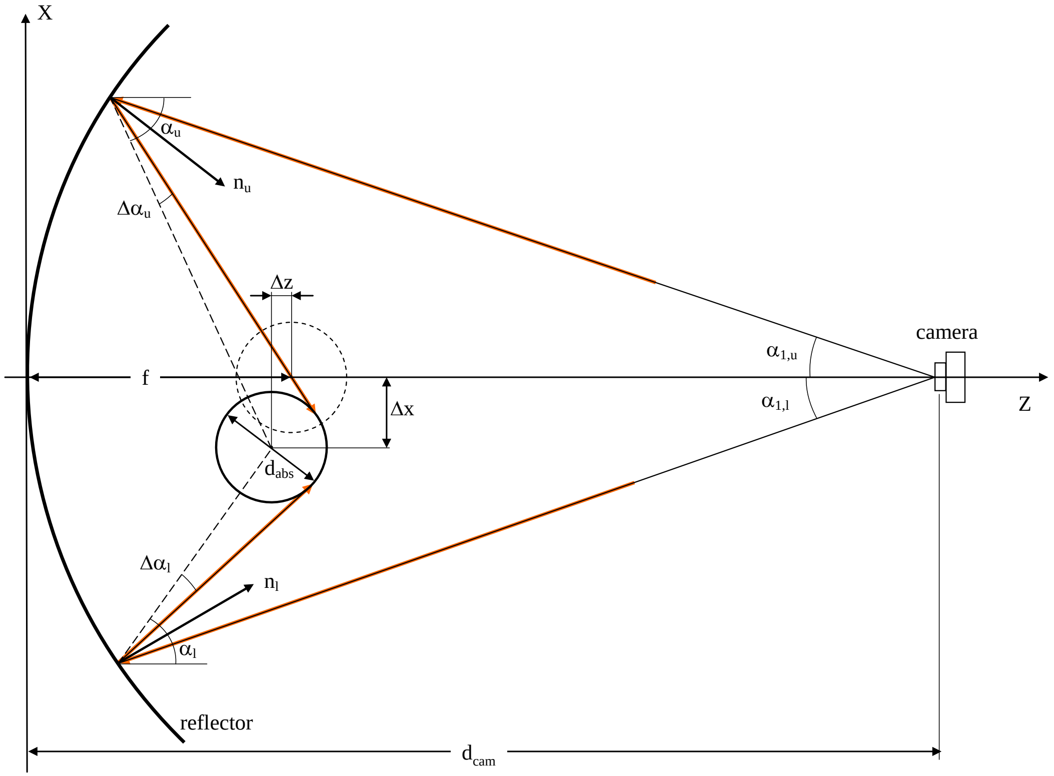
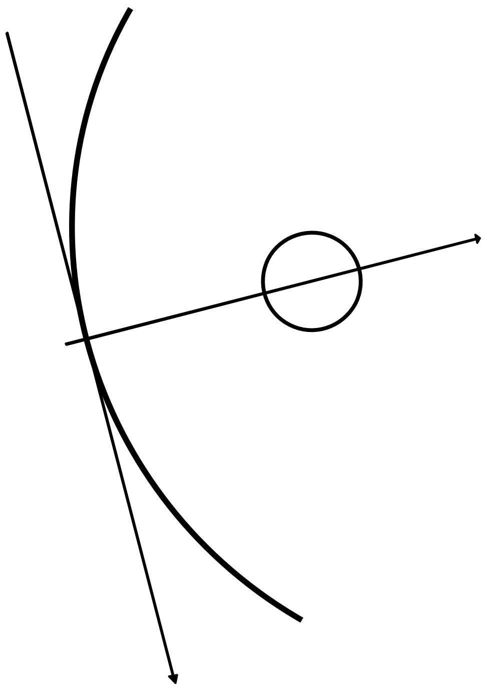
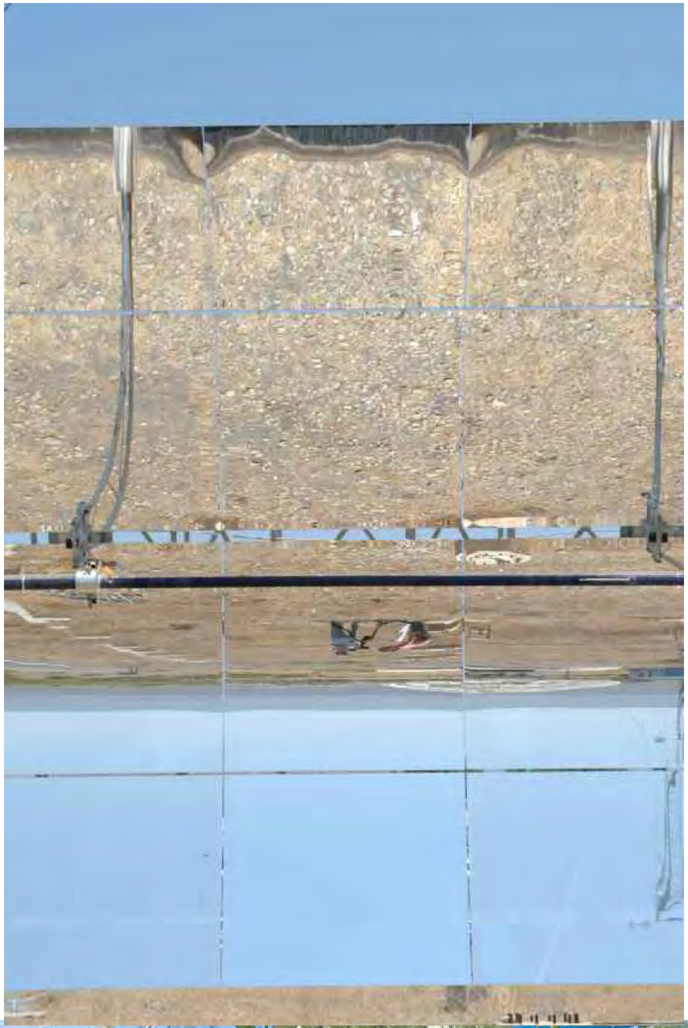
TARMES (Trough Absorber Reflection Measurement System): Basic idea and set-up of measurement system

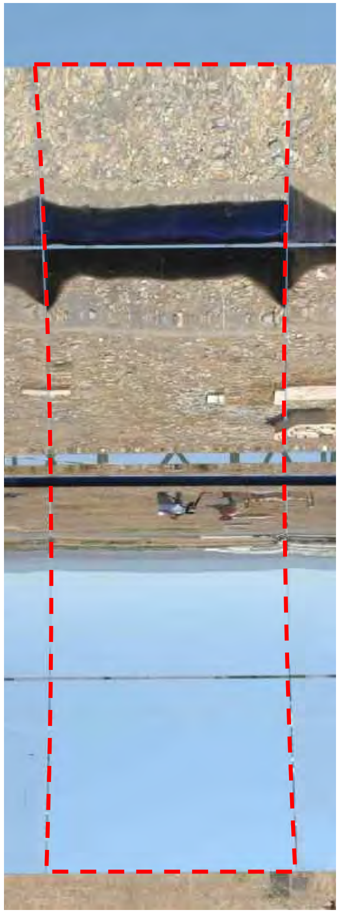


Measurement:
Turning of collector with camera at close distance (~17m)

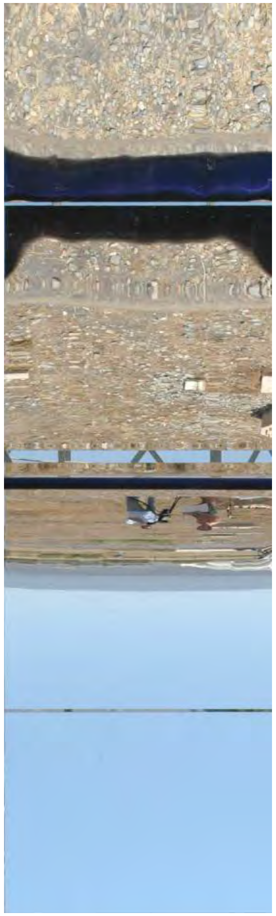




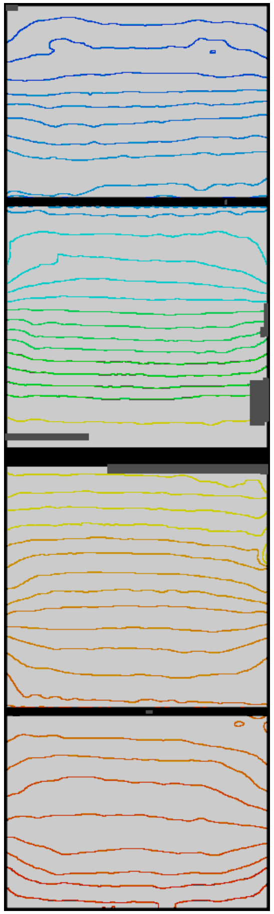
Evaluation



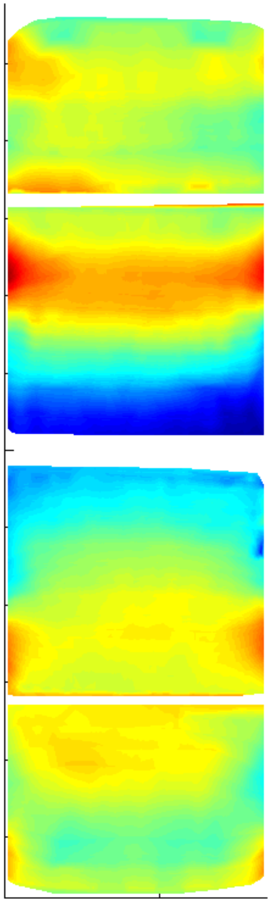
- *Correction of lens distortion*
- *Image rectification*



- *Image treatment*
- *Edge detection*



- *Input of geometrical set-up*
- *Calculation of slope errors*



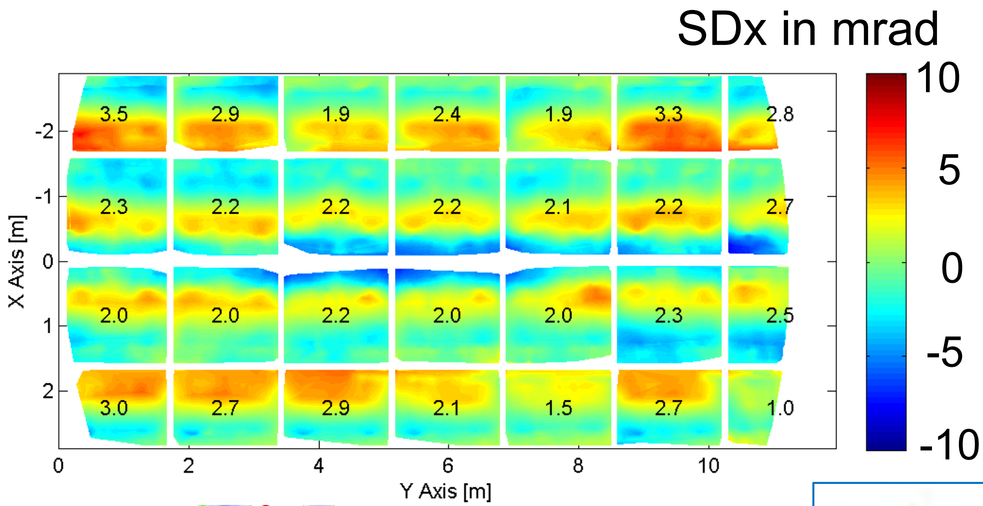
QFly – airborne prediction of the optical performance of parabolic trough collector fields

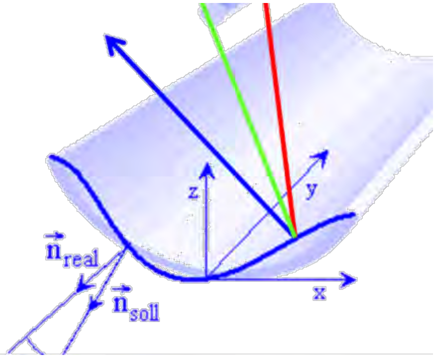
4. QFly - High Resolution
Raw Data

Individual unprocessed photos in 5 min. time lapse:

4. QFly - High Resolution

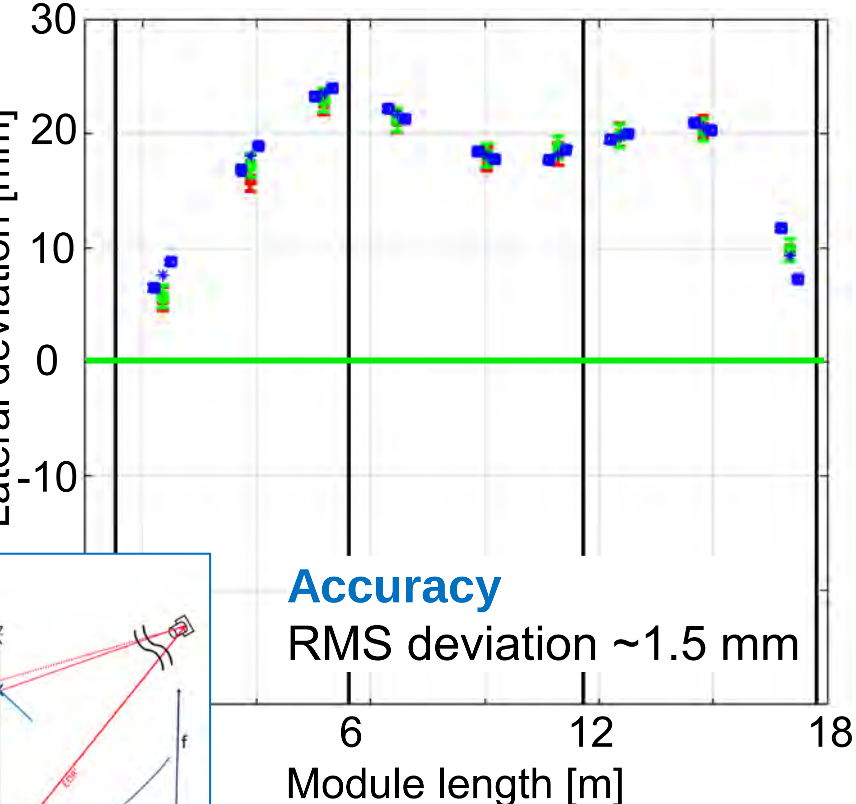
Result: Mirror Shape Maps

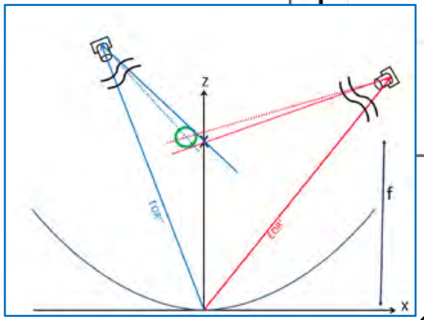




Accuracy
RMS 0.1 mrad
Local ±1 mrad

Result: Absorber Position

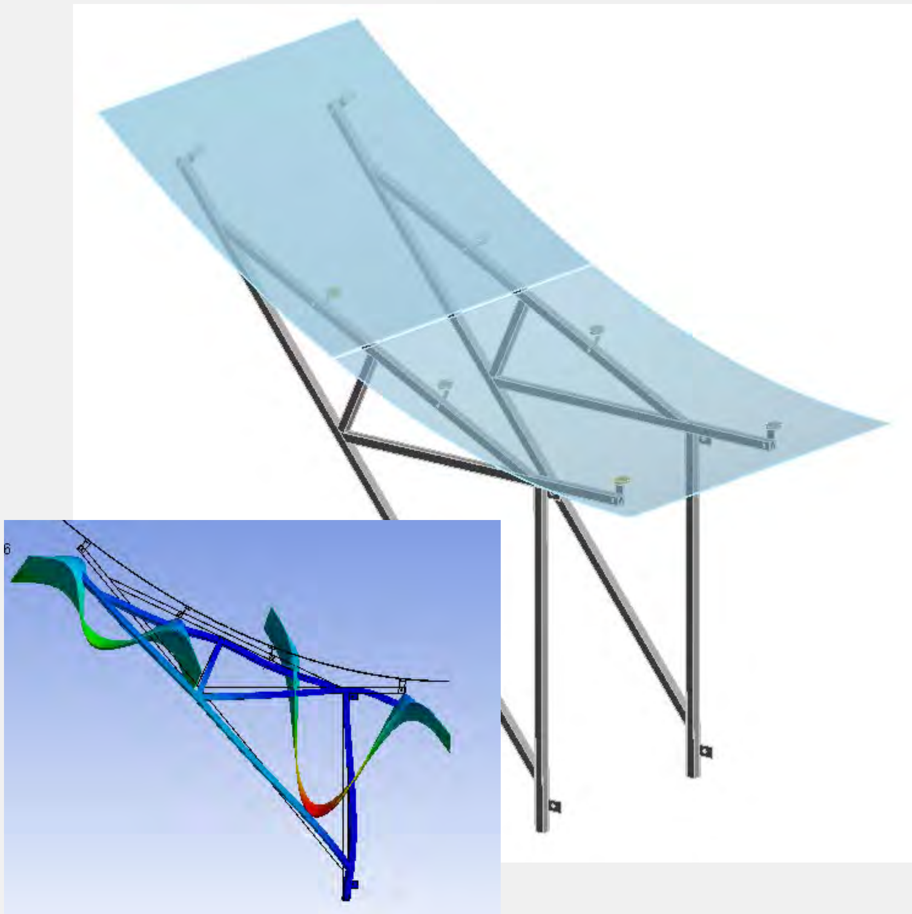


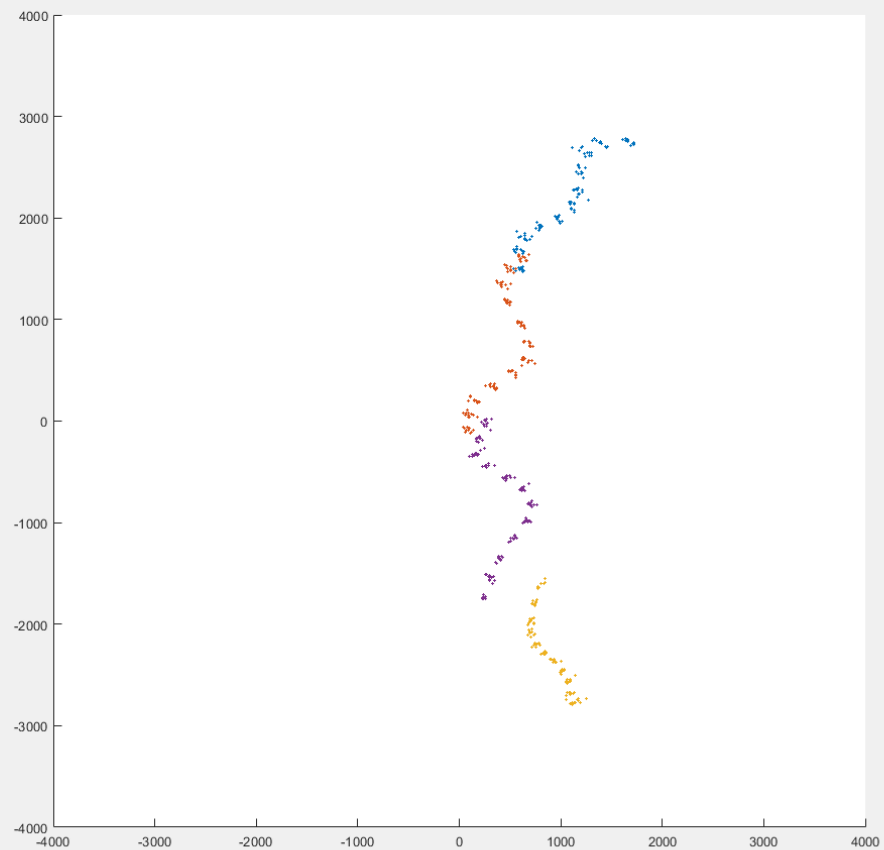


Accuracy
RMS deviation ~1.5 mm

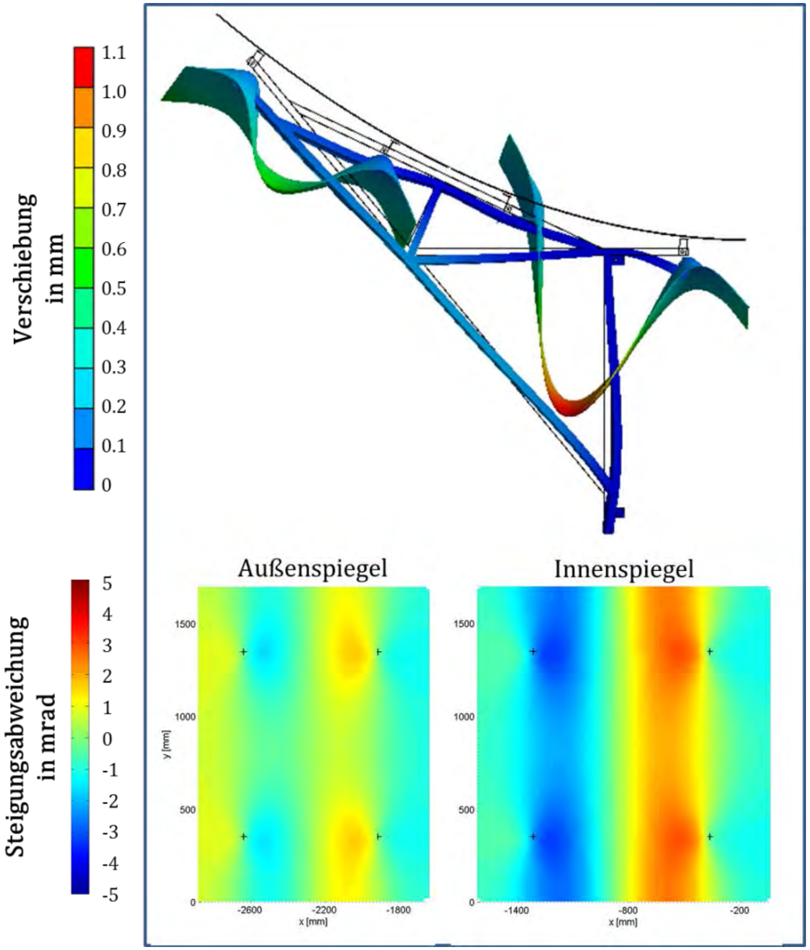
Raytracing software to determine intercept / optical performance

Gravity Load on Parabolic Trough Refectors



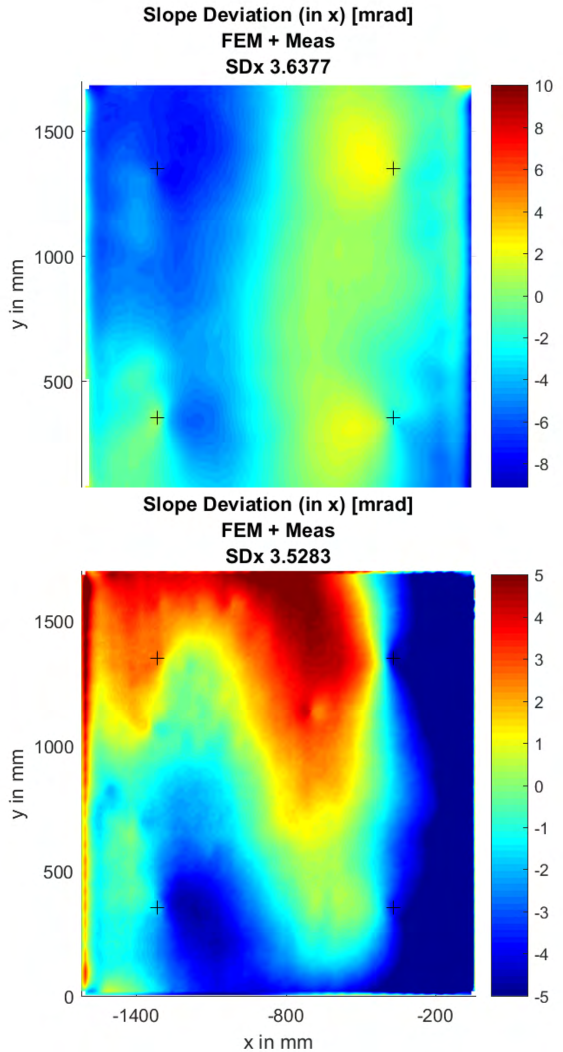


Photogrammetry to measure shape

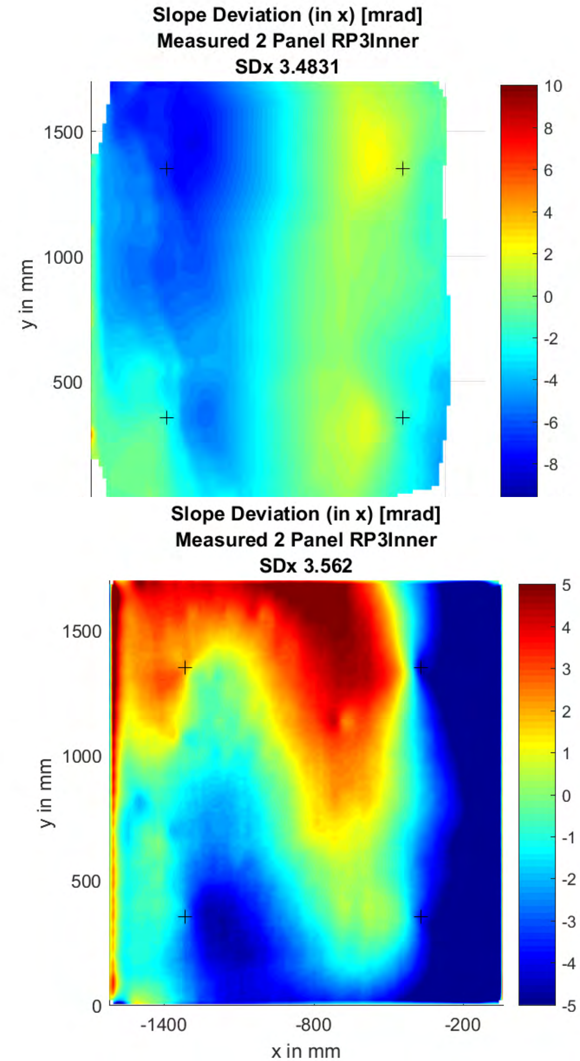


Facet mounted in collector

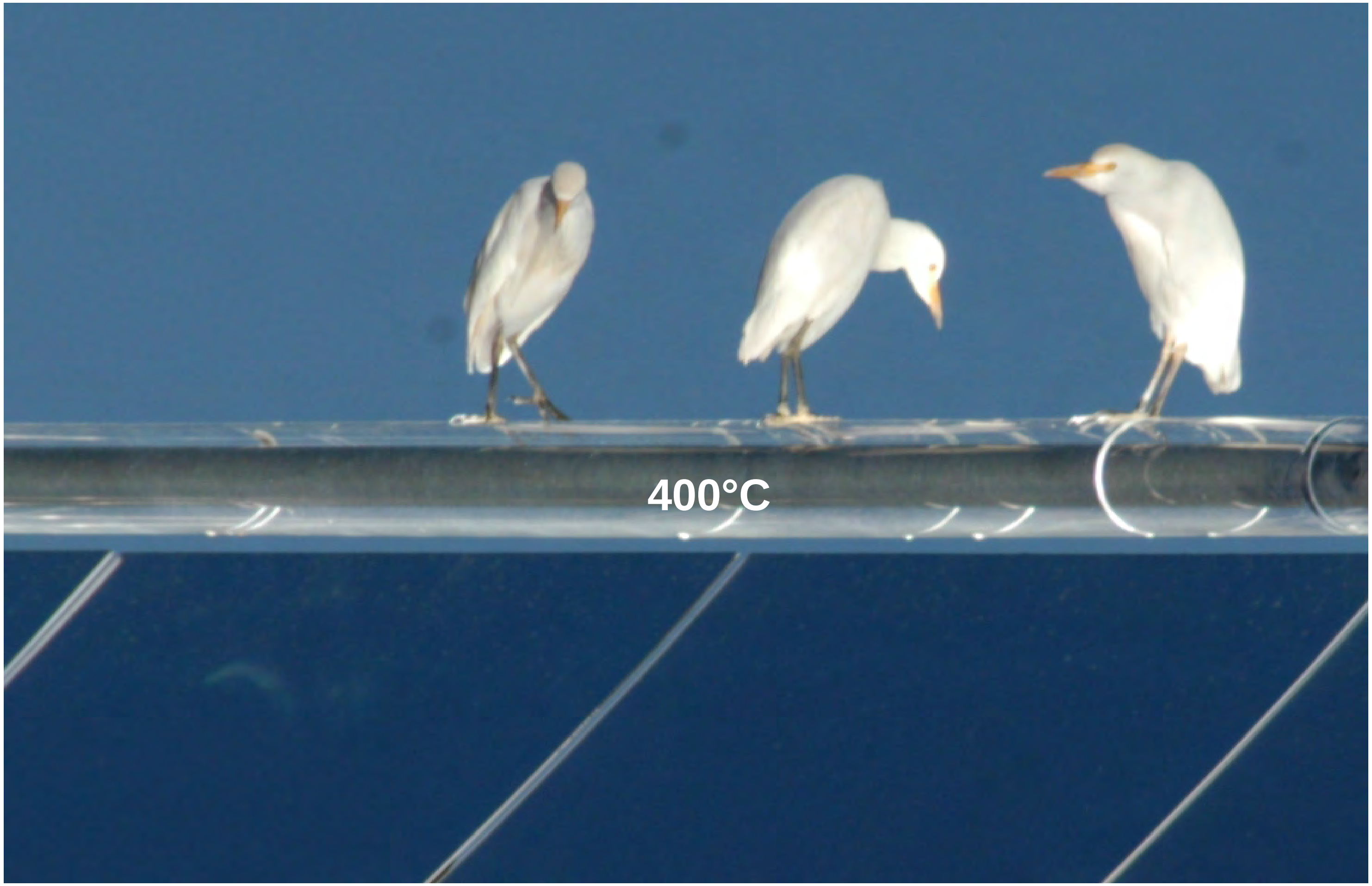
Simulation



Measurement



Final quality inspection …



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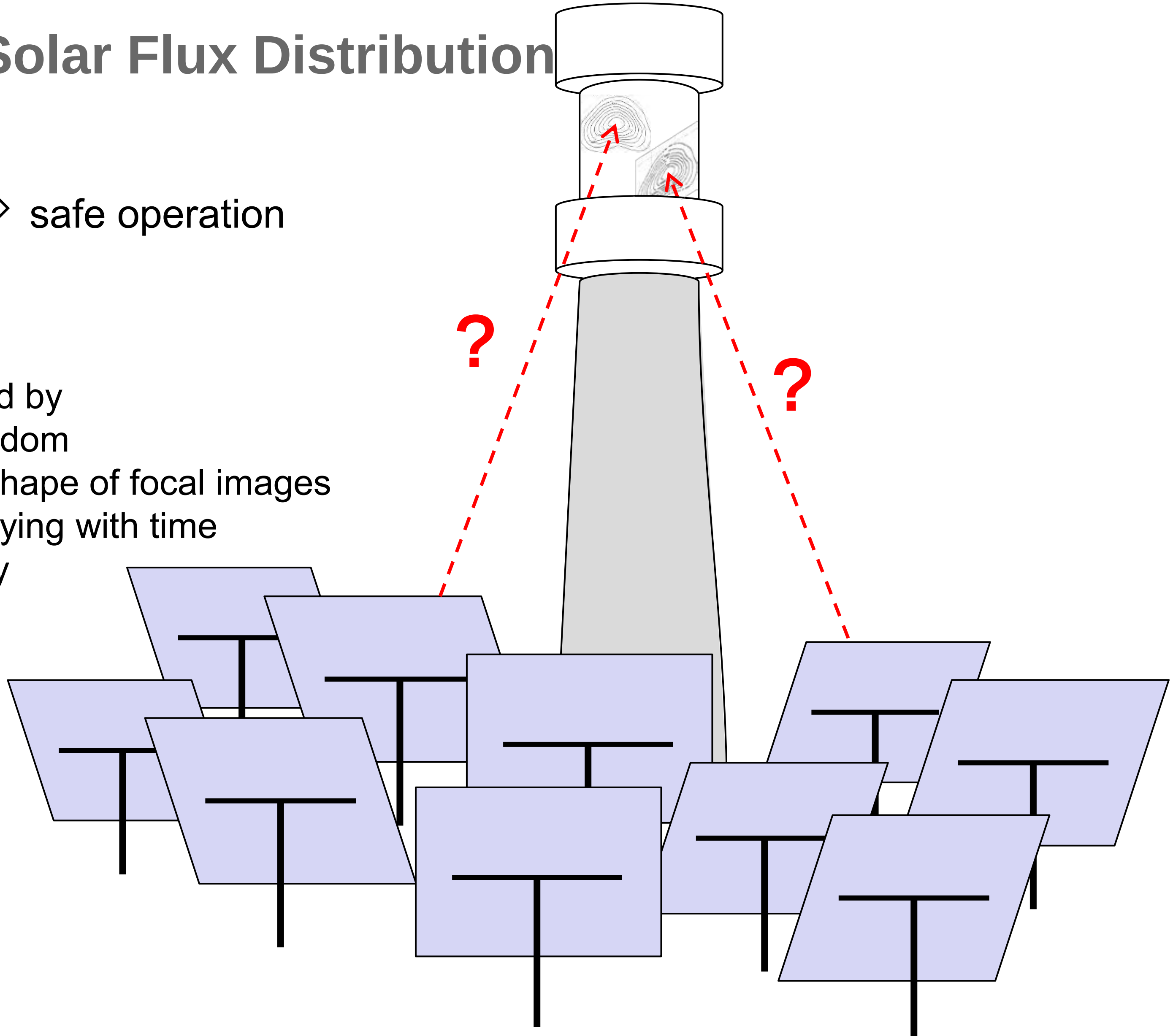
Controlling the Solar Flux Distribution

optical efficiency ⇔ safe operation

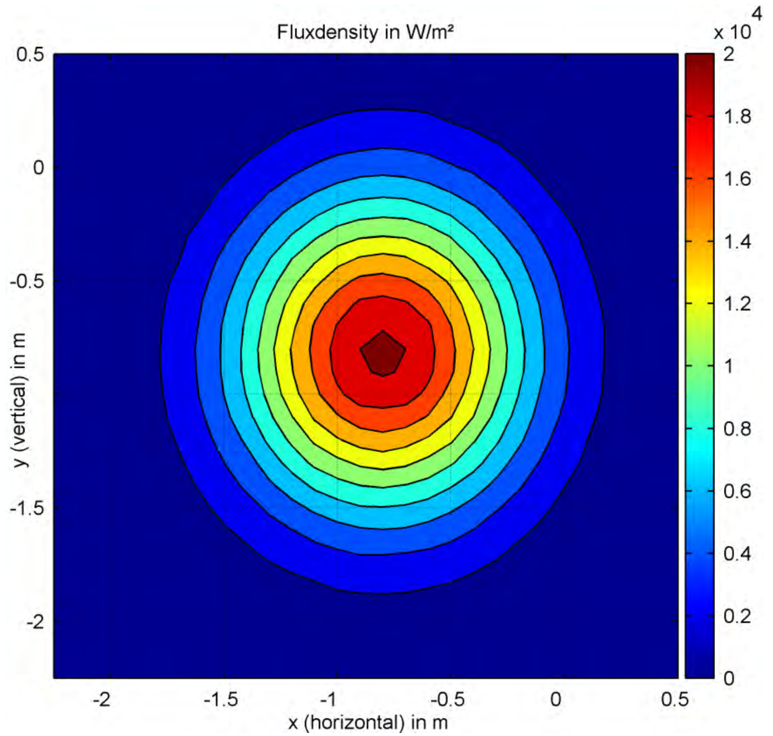
problem is complicated by

- high degree of freedom
- different size and shape of focal images
- size and shape varying with time
- tracking uncertainty

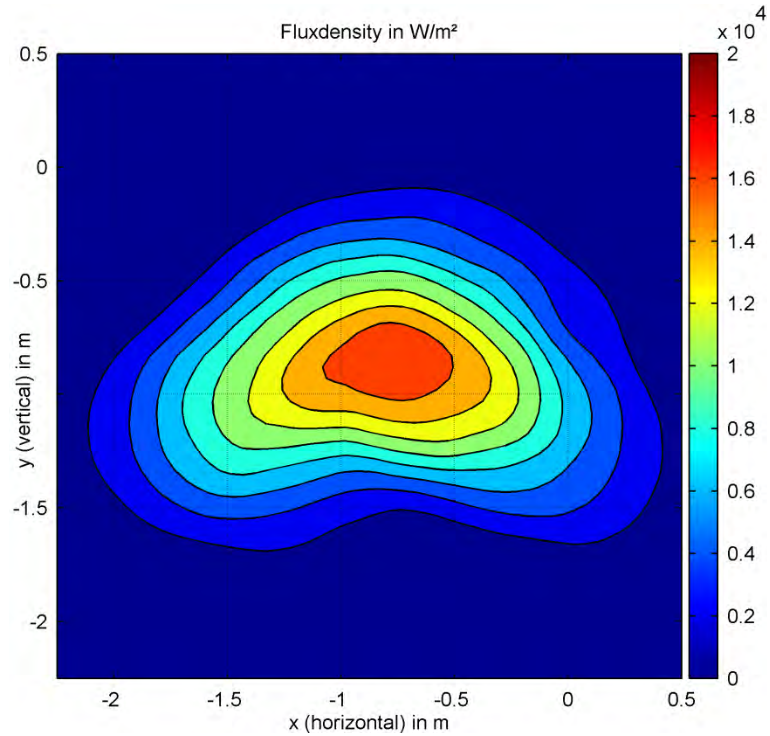


2. State of the Art

Measured vs. simulated flux density distribution of a single heliostat:



simulated with a statistical mirror error

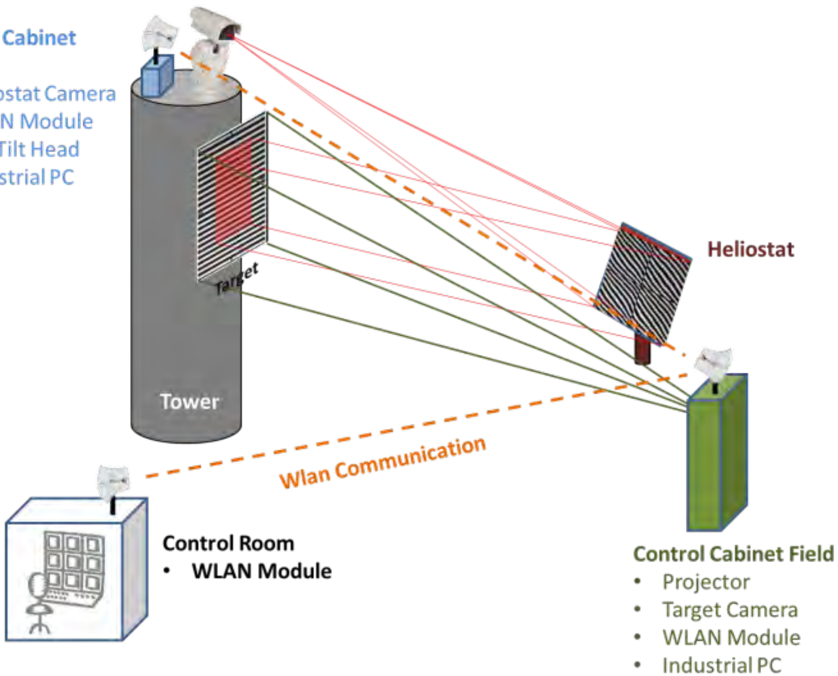


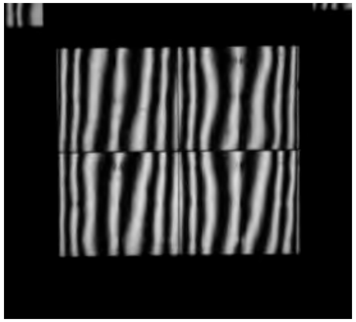
measured

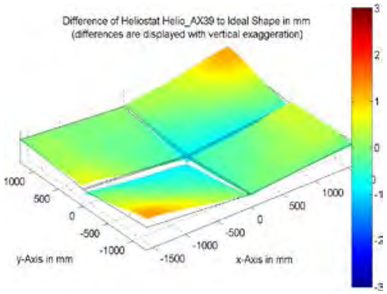
⇒ **low conformity between reality and simulation**

Measurement of Heliostat Slope using Deflectometry

Automated deflectometry measurement system

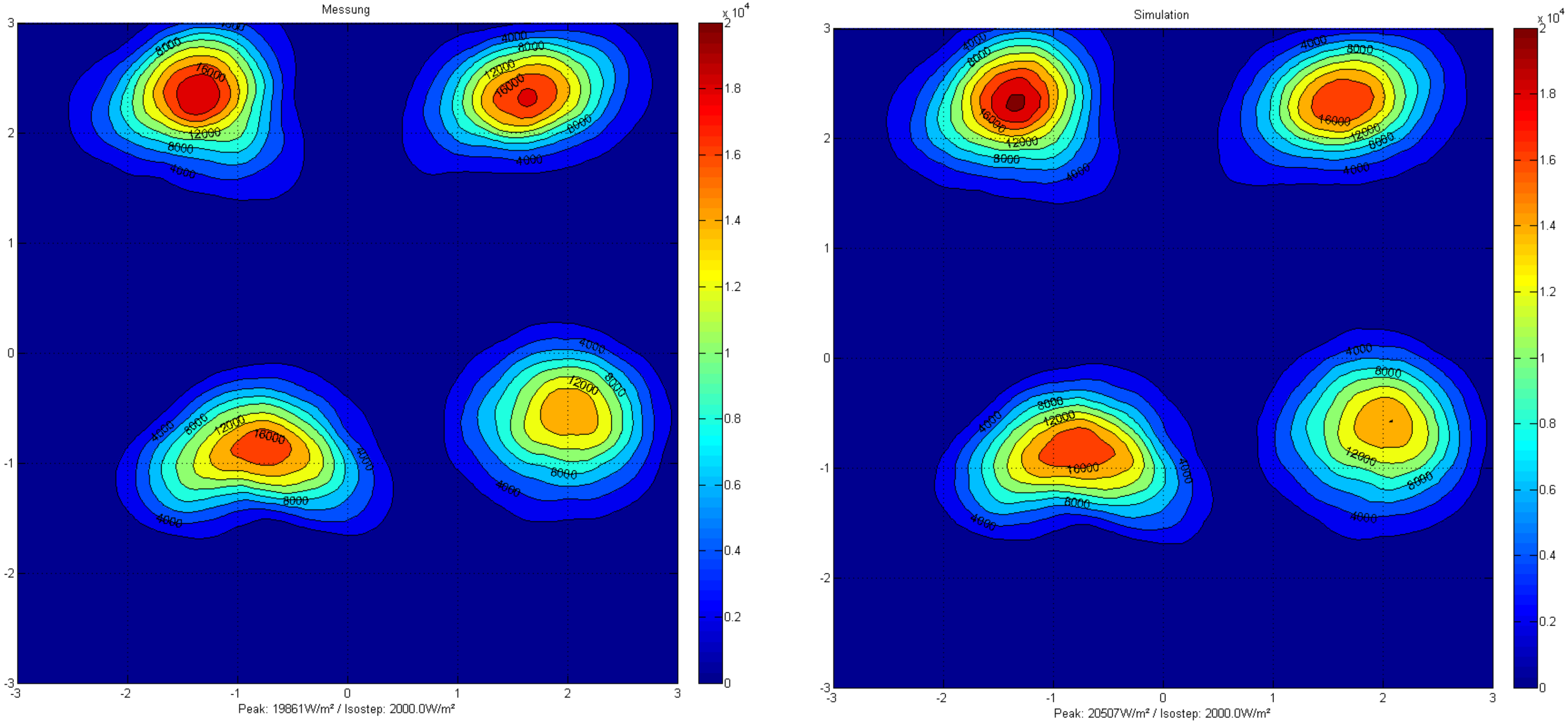






- automatic selection of single heliostats/groups
- automatic measurement and data processing
- performance: ~60sec./hel.

Validation by Comparison of Ray Tracing Calculations to Flux Measurement Data



Flux Measurement

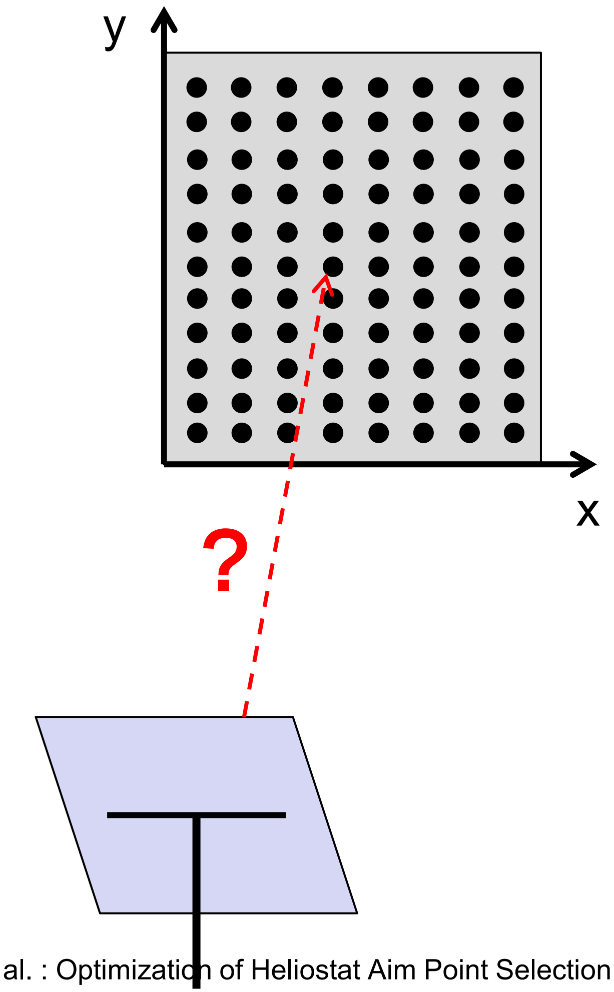
Simulation

Optimization of Heliostat-Aim Point Assignment

continuous optimization: $dim(S) = 2 \cdot n_H$

discrete optimization: $|S| = {n_Z}^{n_H}$

→ Ant Colony Optimization Meta-Heuristic (ACO)*



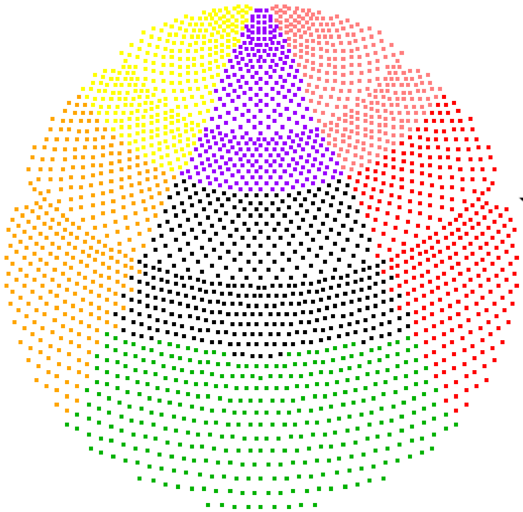
Natural Role Model:

- Ants excrete pheromone on their trails
- Pheromone on the trails evaporates over the time
- Ants chose their way randomly mixed with a kind of short visibility (myopic)
- Ants are strongly attracted by pheromone

	H1	H2	H3	H4	…	Hn_H
A1	11	12	13	14	…	$1n_H$
A2	21	22	23	24	…	$2n_H$
…	…	…	…	…	…	…
An_Z	n_Z1	n_Z2	n_Z3	n_Z4	…	n_Zn_H

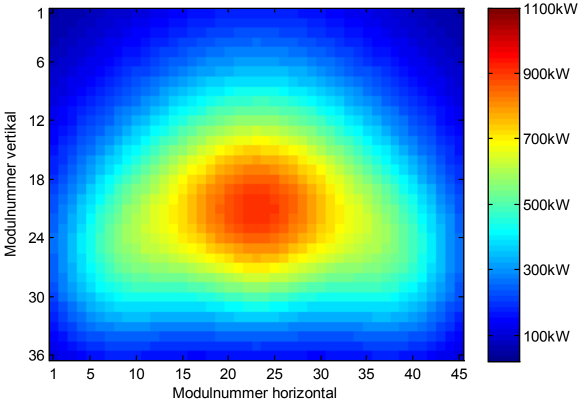
*Belhomme, B.et al. : Optimization of Heliostat Aim Point Selection for Central Receiver Systems Based on the Ant Colony Optimization Metaheuristic. Journal of Solar Energy Engineering, 2014. 136(1).

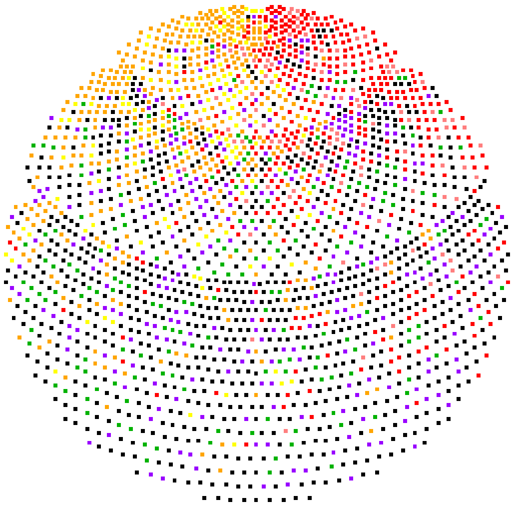
Aim Point Optimization @ Solar Tower Jülich



Reference Case:
Operator's experience

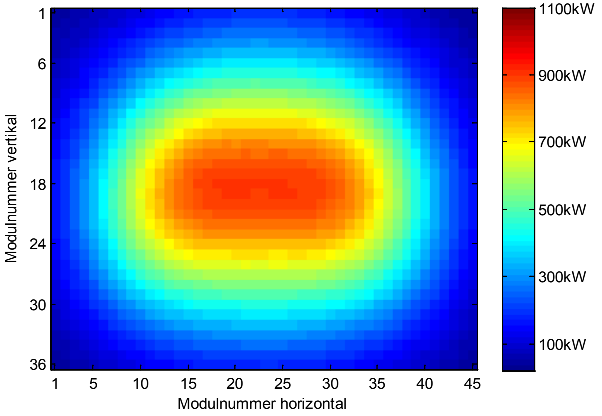
Power Output = 100%





Intercept – Optimization

Power Output ***111.31 %***



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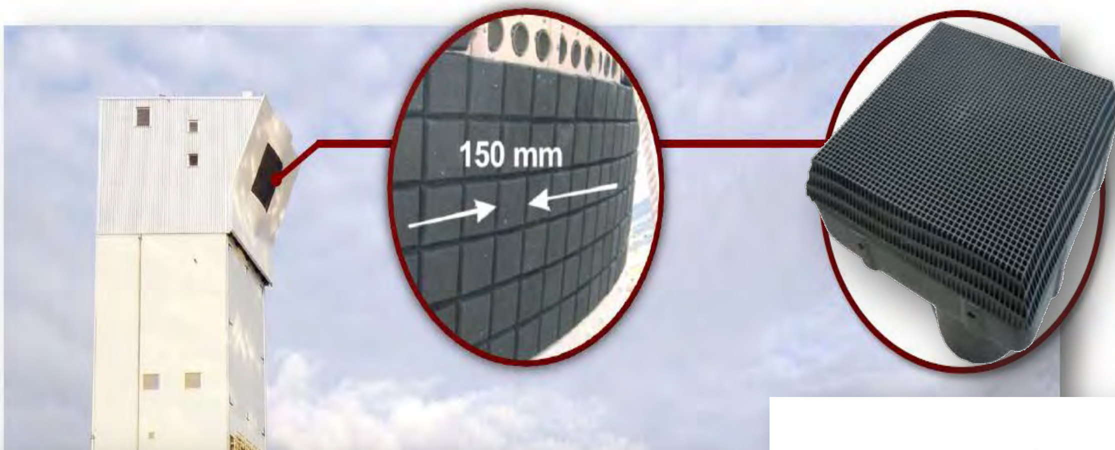
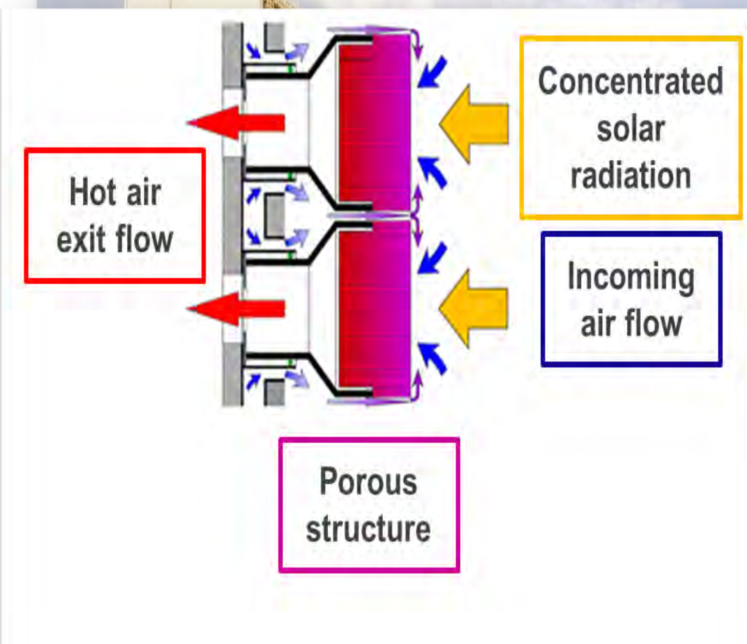
   - **Stable and efficient volumetric receivers**

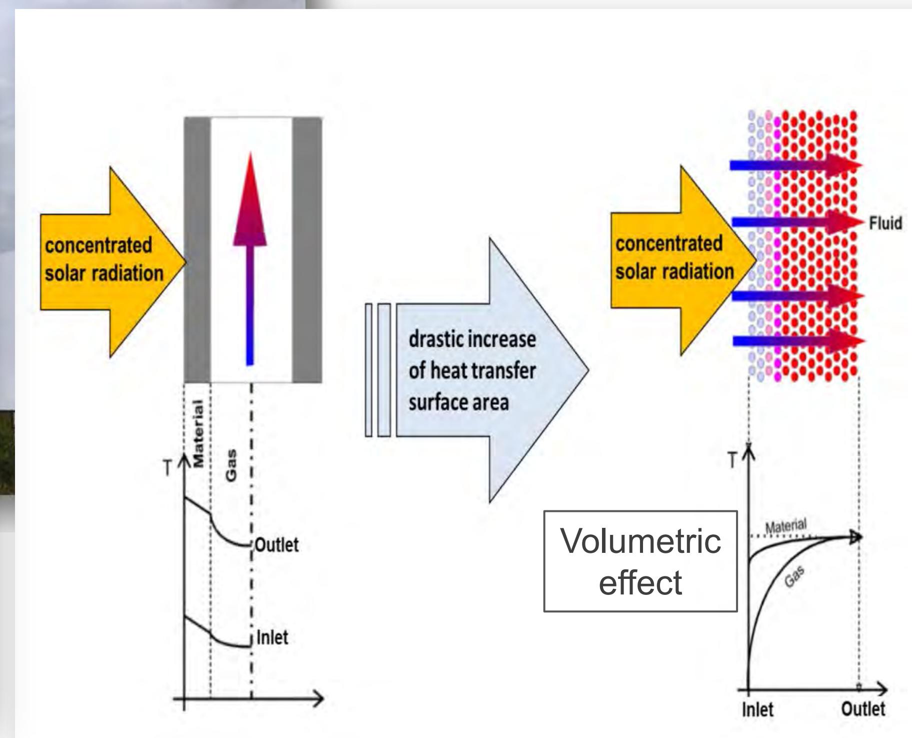
5. Conclusions

Energy from the sun: Open volumetric solar receiver



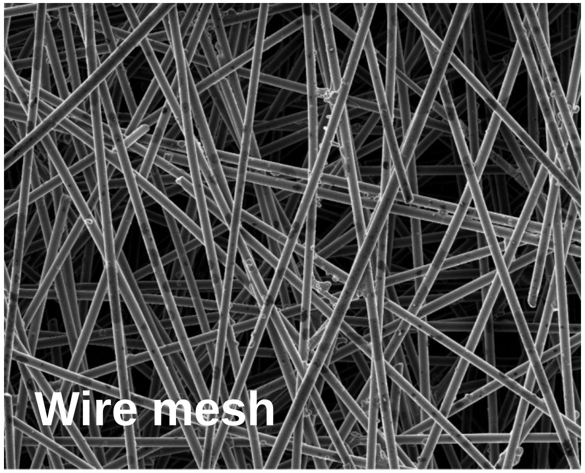
HiTRec-II
SiSiC
honeycomb



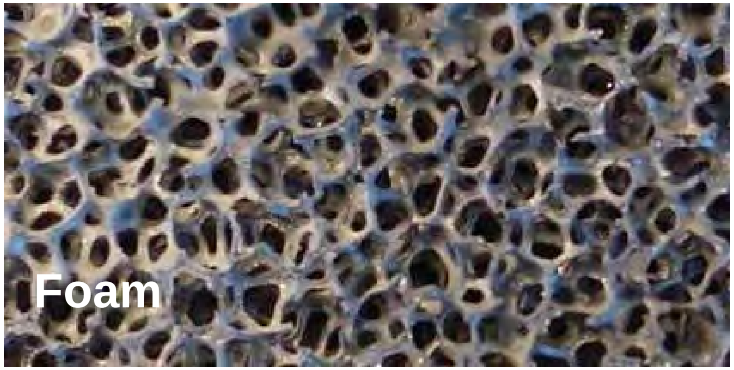


Source: dlr.de

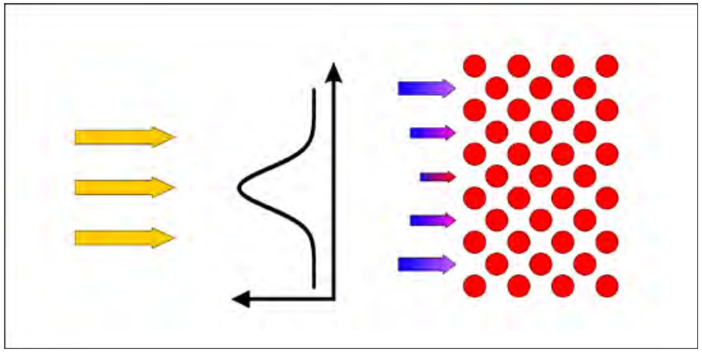
What is the perfect absorber?



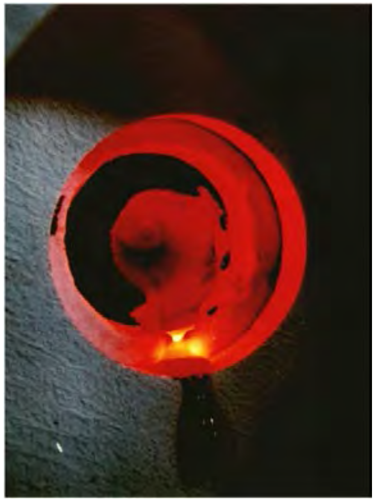
600µm Ceramat FN Oberfläche x100



Different Characteristics affecting Flow Stability



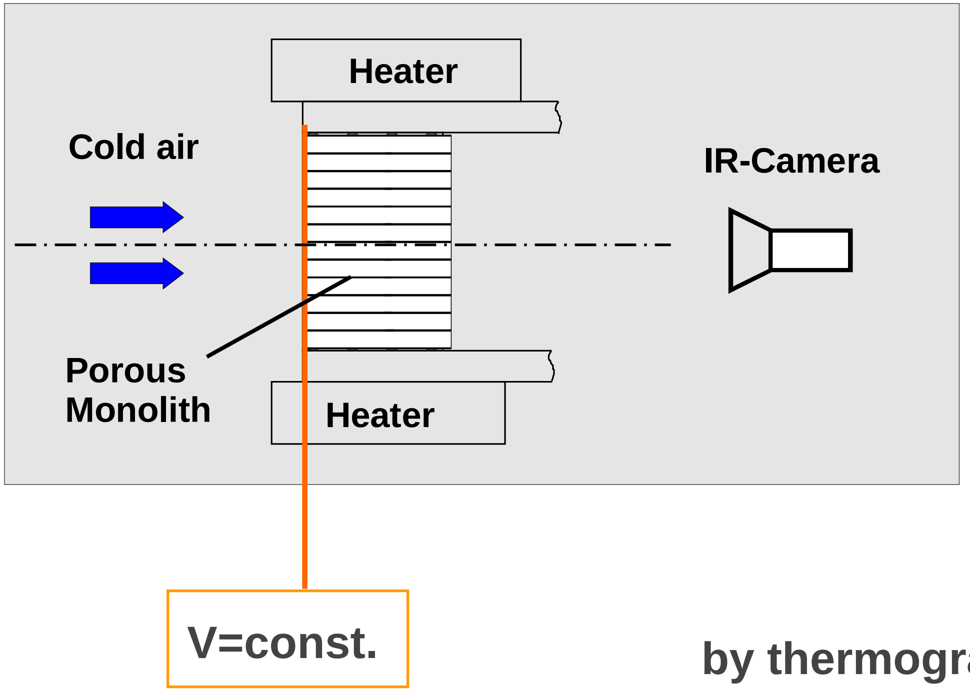
- viscosity increases with increasing temperature
- hot zones are badly cooled

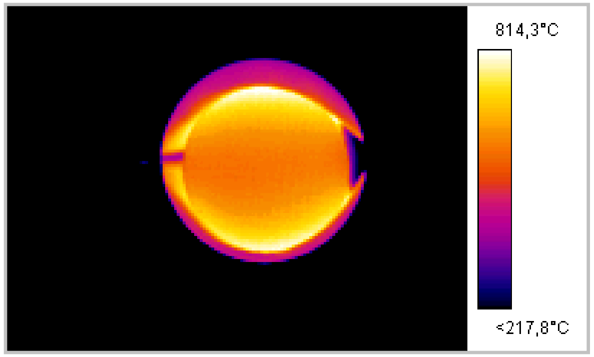


- local hot spots
- → instable flow at
  - high temperatures
  - linear pressure drop characteristics
  - low thermal conductivity

DLR

How can instable flow be visualized?

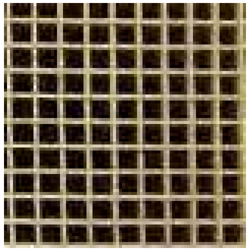


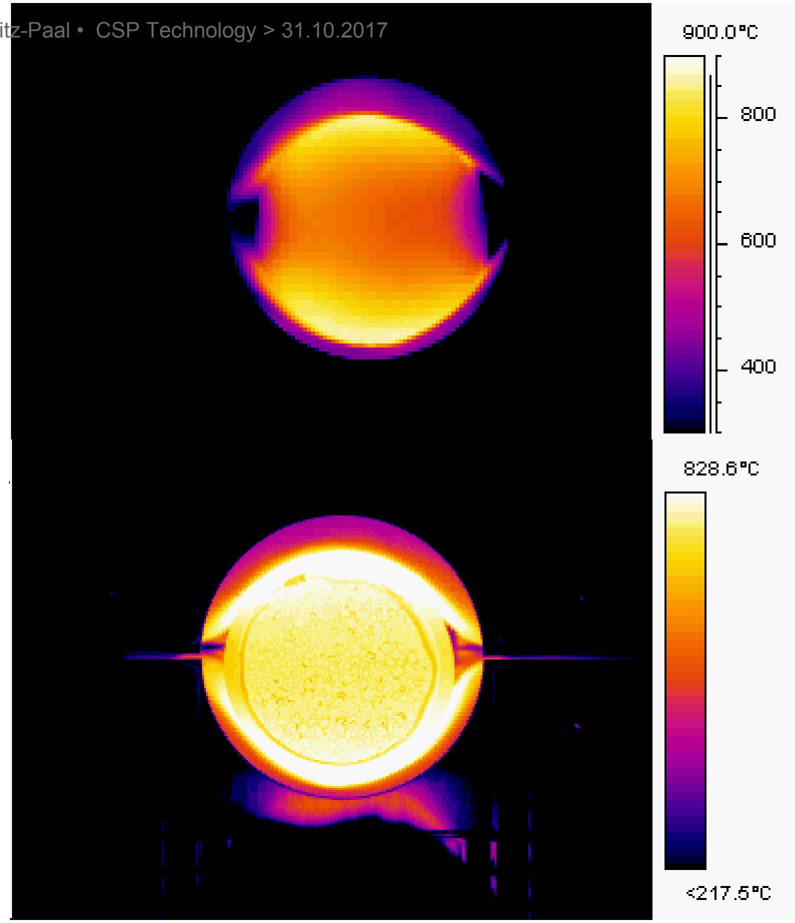


by thermograph monitoring of

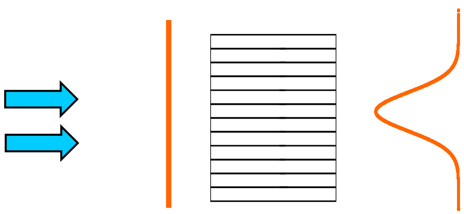
the cooling of a heated porous monolith

cordierite honey comb





SiC foam



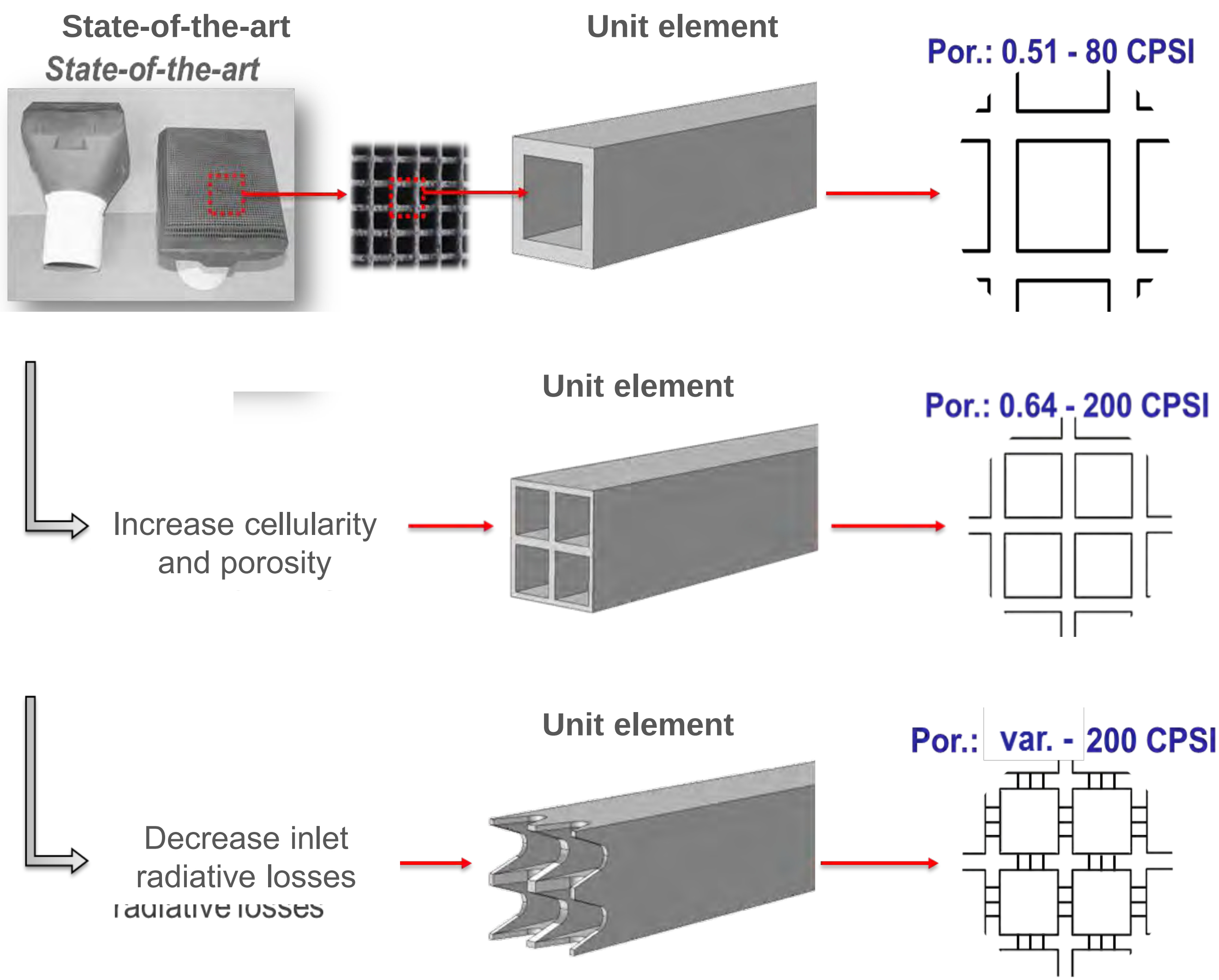
v = const.

v = 0 in hot channels

geometry/pressure loss characteristics influences flow stability

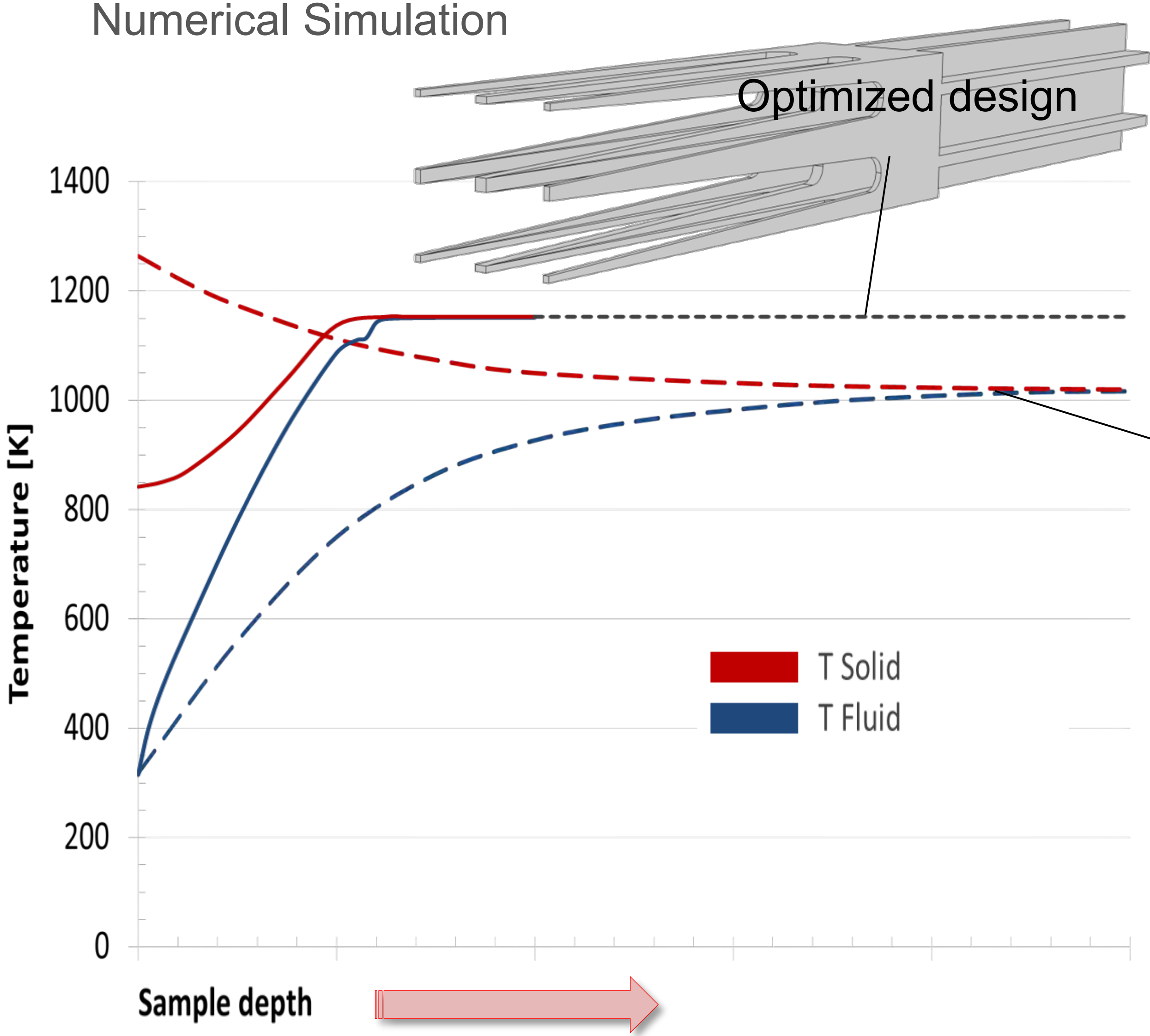
heat conductivity influences flow stability

Optimizing the Absorber Design



Optimizing the Absorber Design

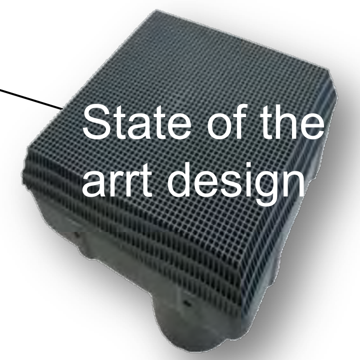
Numerical Simulation



Innovative geometry

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

η = 90 %



HiTRec-II

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

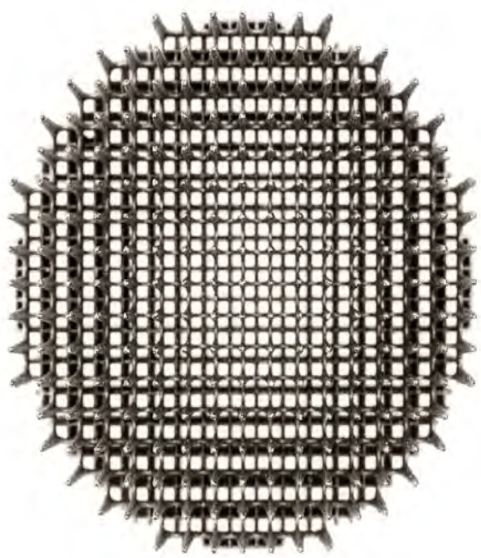
η = 72%

Prototype sample production by 3D printing

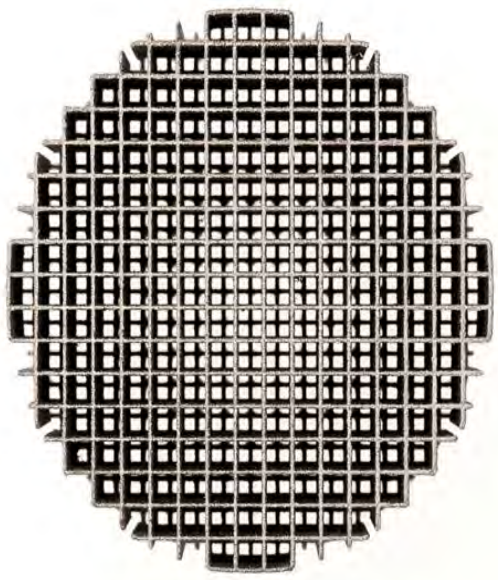
Cylindrical prototype test-sample: Ti6Al4V 3:1 scaled up geometry

Front view

Top view



Bottom view

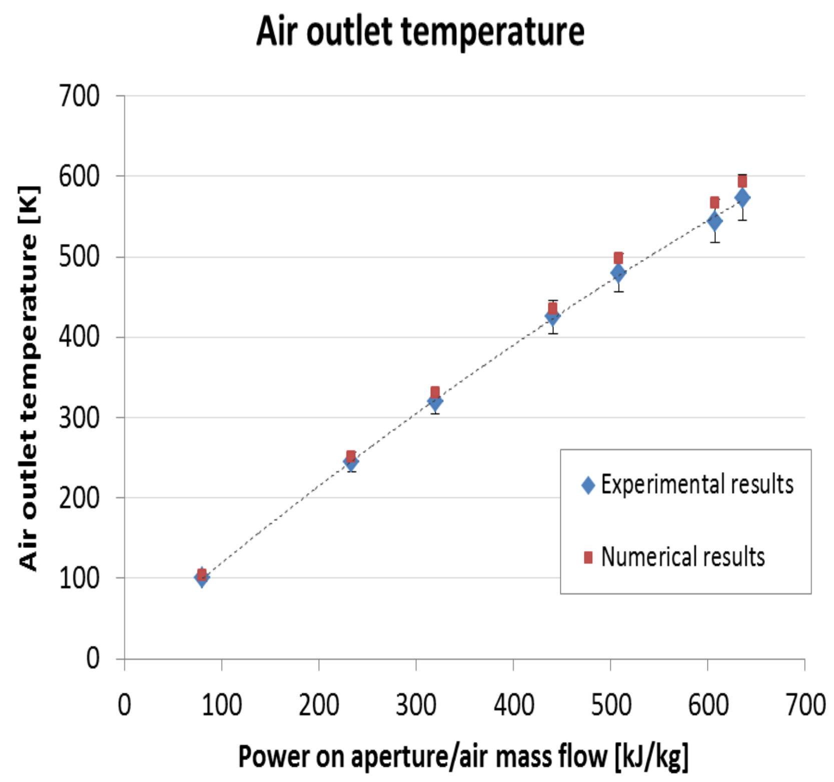


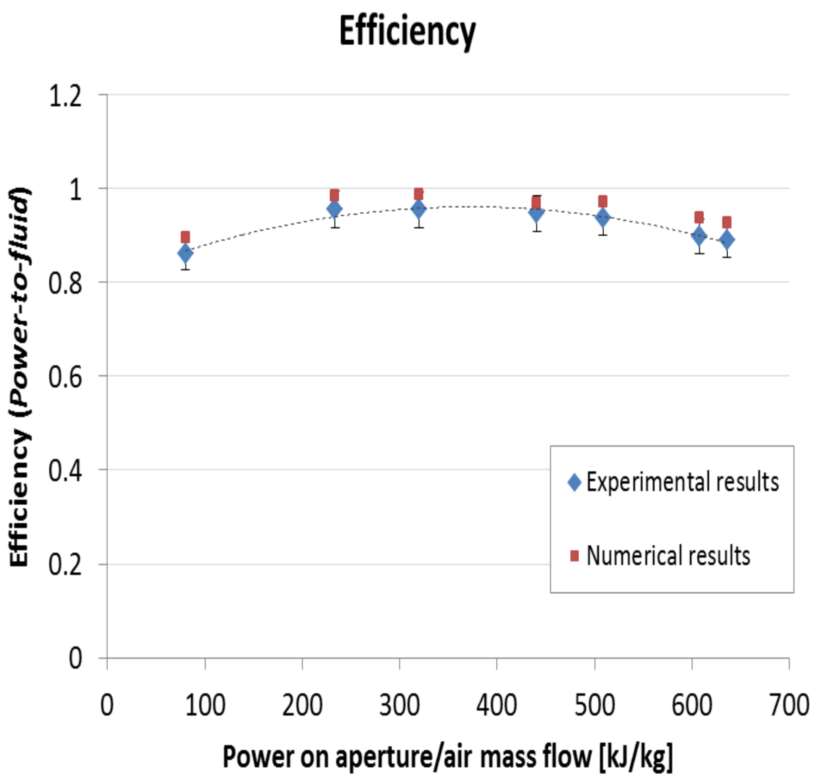
Fraunhofer IFAM

DLR

Experimental Validation of Prototype

Thermal efficiency evaluation → 20 kW solar simulator





Outline

1. Characteristics of CSP

2. Market und Cost Development

3. Benefits for a mix of PV und CSP

4. Scientific Challenges in CSP Development
    - Shape Accuracy of Solar Concentrators
    - Controlling the Solar Flux Distribution
    - Stable and efficient volumetric receivers

5. **Conclusions**

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

- Today we better understand how to measure, model and optimize
  - large solar fields of parabolic troughs and heliostats,
  - solar receivers and storage systems with different heat transfer fluid,
  - the impact of environmental effects like sunshape and aerosols to maximize the performance and lifetime of a CSP plant.

- 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