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 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

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Since 2003, more volumetric receivers in DLR.

Global expansion of CSP in three phases

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2003 DLR Head of Division and Prof. @RWTH Aachen

Global expansion of CSP in three phases

2006: 1.5 MW volumetric receiver demo plant planned with research & industry

Global expansion of CSP in three phases


2008 QUARZ®: DLR Qualification Lab for Solar Components
Global expansion of CSP in three phases

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

Global expansion of CSP in three phases

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

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 24/7 electricity

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

#### Scenario 1

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<thead>
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<th>Social acceptance</th>
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#### Installed Capacity

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

![Graph showing installed capacity for different energy sources over time](image-url)
Chile Scenario Results – Expansion Model
Scenario 1

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Social acceptance, Energy demand, Technological change in BESS, Externality costs, RE investment costs, Fossil fuel costs, CSP LCOE.

Generation

2029

PV

CSP

[Graph showing generation from 2016 to 2050, with labels for Battery, Pump, Diesel, PV_Solar, 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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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 Parabolic Trough 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
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

QFly UAV
4. QFly - High Resolution
Raw Data

Individual unprocessed photos in 5 min. time lapse:
4. QFly - High Resolution

Result: Mirror Shape Maps

Raytracing software to determine intercept / optical performance

- Accuracy
  - RMS 0.1 mrad
  - Local ±1 mrad

- RMS deviation ~1.5 mm
Gravity Load on Parabolic Trough Refectors
Photogrammetry to measure shape
Facet mounted in collector

Simulation

Measurement

Slope Deviation (in x) [mrad]
FEM + Meas
SDx 3.6377

Slope Deviation (in x) [mrad]
FEM + Meas
SDx 3.5283

Slope Deviation (in x) [mrad]
Measured 2 Panel RP3Inner
SDx 3.4831

Slope Deviation (in x) [mrad]
Measured 2 Panel RP3Inner
SDx 3.562
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**: simulated with a statistical mirror error
- **Measured**: 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

Aim Point Optimization @ Solar Tower Jülich

Reference Case: Operator’s experience
→ Power Output = 100%

Intercept – Optimization
→ Power Output 111.31%
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Energy from the sun: Open volumetric solar receiver

HiTRec-II
SiSiC honeycomb

Source: dlr.de
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

geometry/pressure loss characteristics influences flow stability

heat conductivity influences flow stability

\( v = \text{const.} \) in hot channels

\( v = 0 \)
Optimizing the Absorber Design

State-of-the-art

Increase cellularity and porosity

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

- **HiTRec-II**
  - $T_{\text{air-out}}$: 1012 K
  - $\eta = 72\%$

Graph showing temperature profiles for solid and fluid phases at different sample depths.
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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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