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Metal Oxide Cycles: Reactor Development

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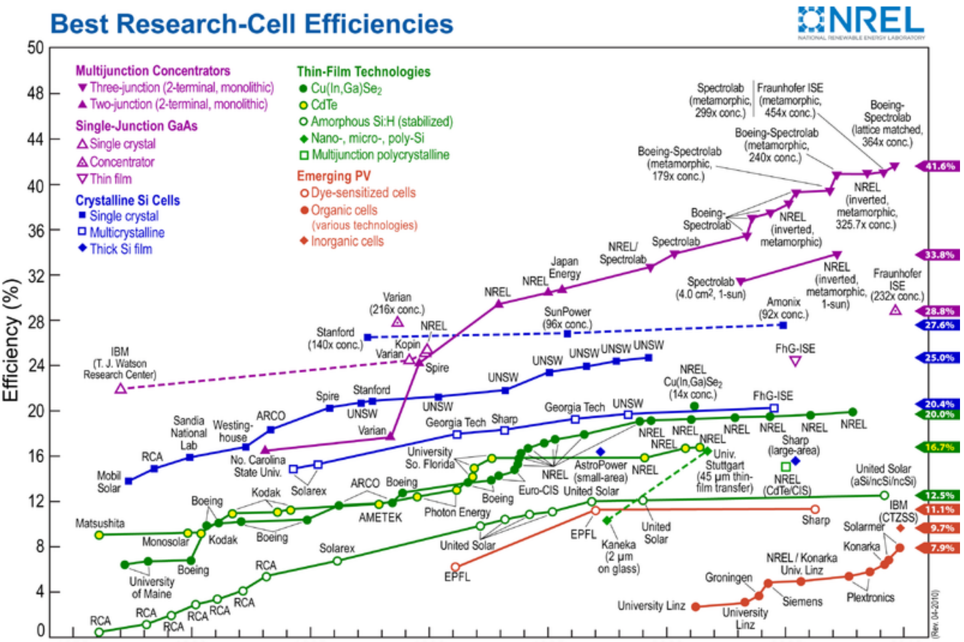
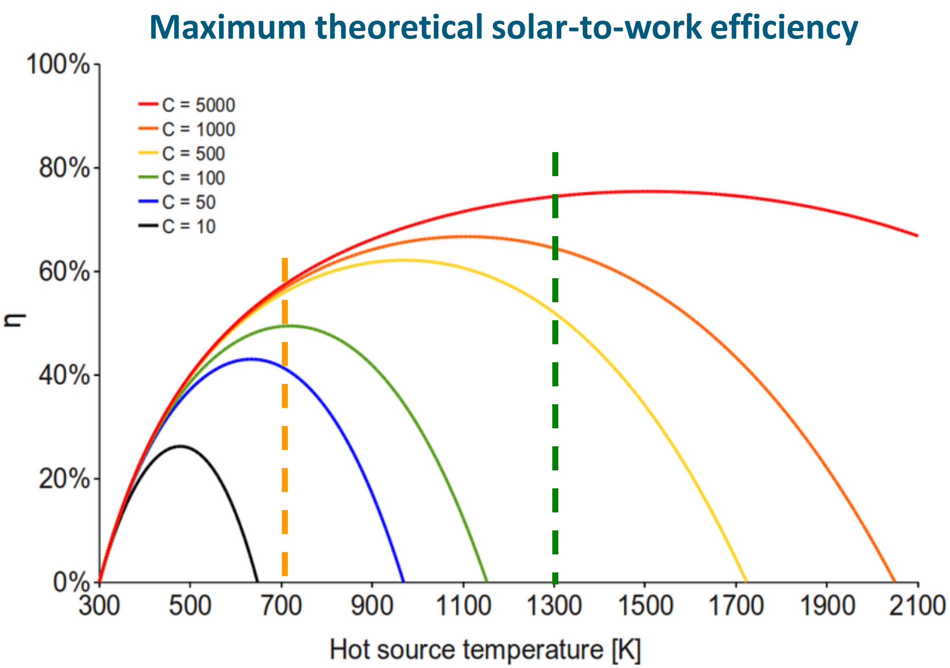
Big Picture Renewable H_2: Pathways and Challenges

Electrochemical vs. Thermochemical

sun→(concentrator)→PV cell→electrolyzer→H_2



sun→concentrator→reactor→H_2



- PV cell cost and efficiency
- Electrolyzer cost and efficiency
- Concentrator cost and efficiency
- Limit: quantum mechanics (band gaps)

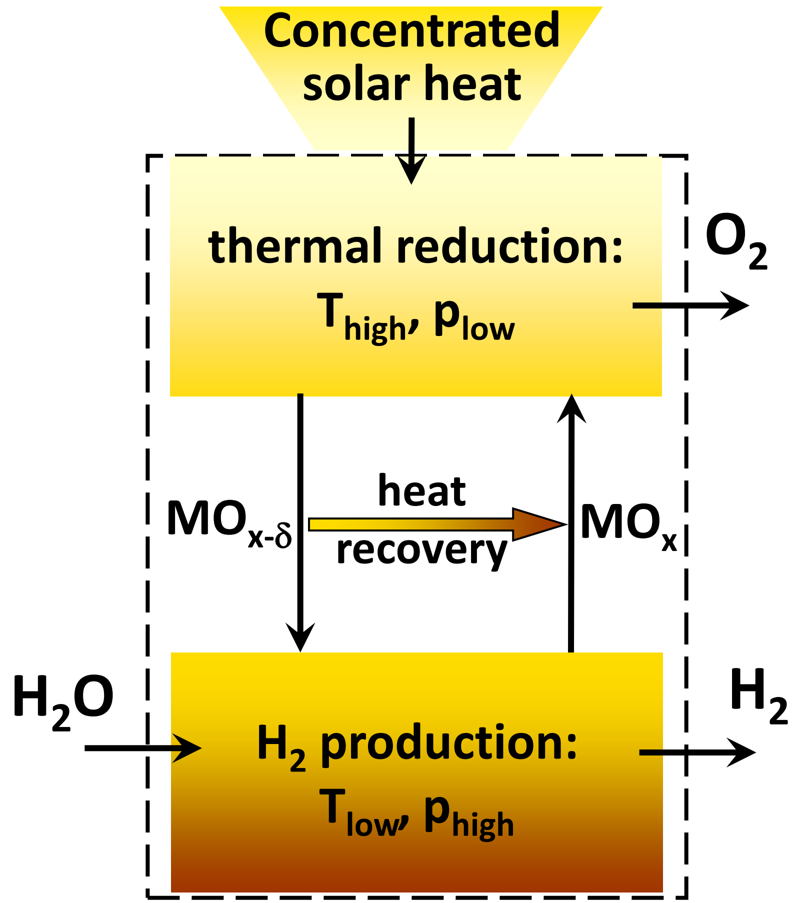
- Concentrator cost and efficiency
- Reactor cost and efficiency
- High temperature operation
- Thermodynamics: Low T→ low efficiency

The Big Picture Challenge: Maximize efficiency/levelized cost

Thermochemical H_2: Design Requirements

Key efficiency attributes:

- DIRECT solar absorption by working material
- EFFICIENT heat recovery between T_H & T_L
- CONTINUOUS on-sun operation
- INTRINSIC gas and pressure separation



Two-step metal oxide cycle

Challenge: ***Design*** **a reactor embodying all the key efficiency attributes**

Approach:

- Keep it simple
- Respect the thermodynamics

Particle Bed reactor: Design and Operation

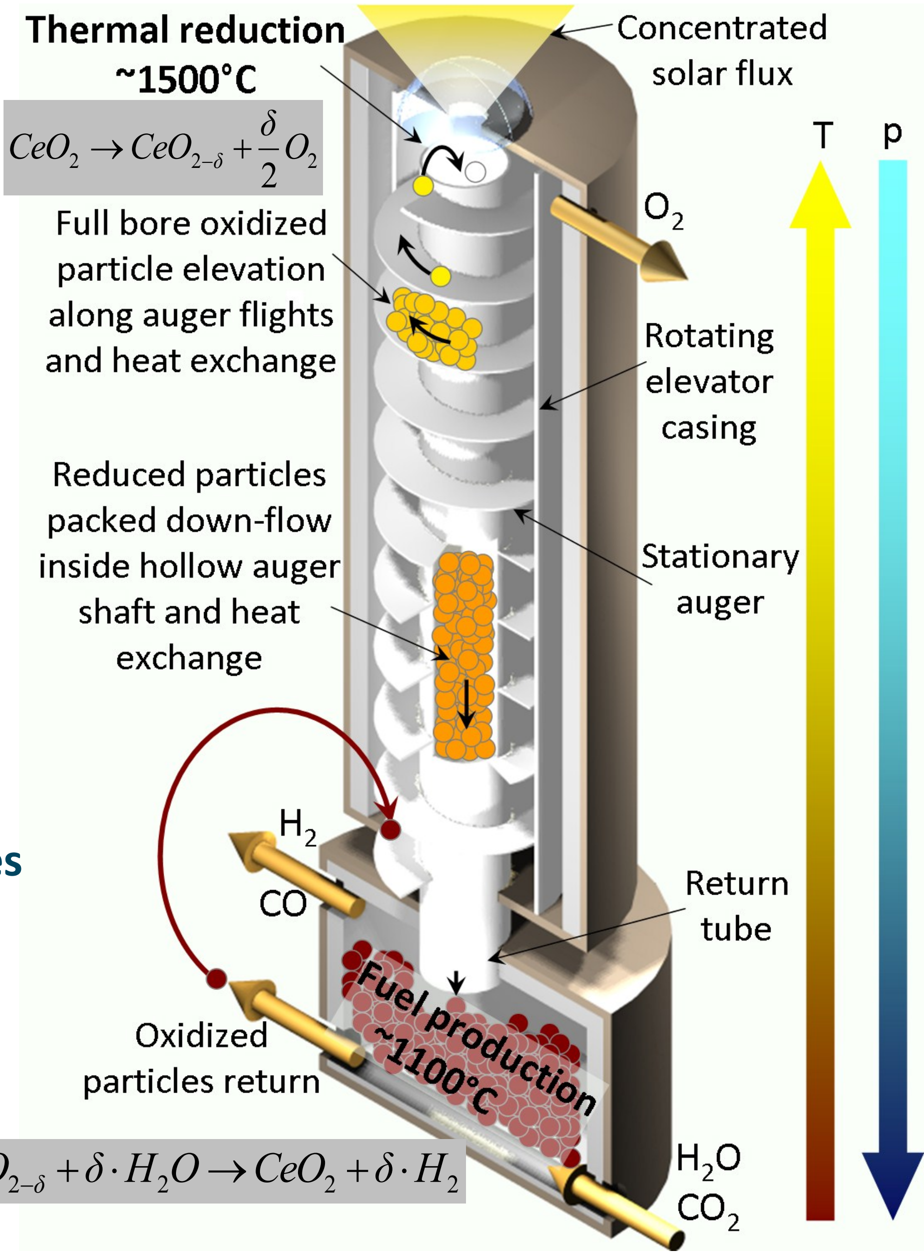
Key efficiency attributes:

- DIRECT solar absorption by working material
- EFFICIENT heat recovery between T_H & T_L
- CONTINUOUS on-sun operation
- INTRINSIC gas and pressure separation

Specific design advantages:

- Small reactive particles (~100µm)
- Only particles are thermally cycled
- Only one high T moving part: a ceramic tube
- Independent component optimization
- Straightforward material replacement
- Uses established high T and vacuum techniques

High performance particle receiver reactor embodies ALL key efficiency attributes

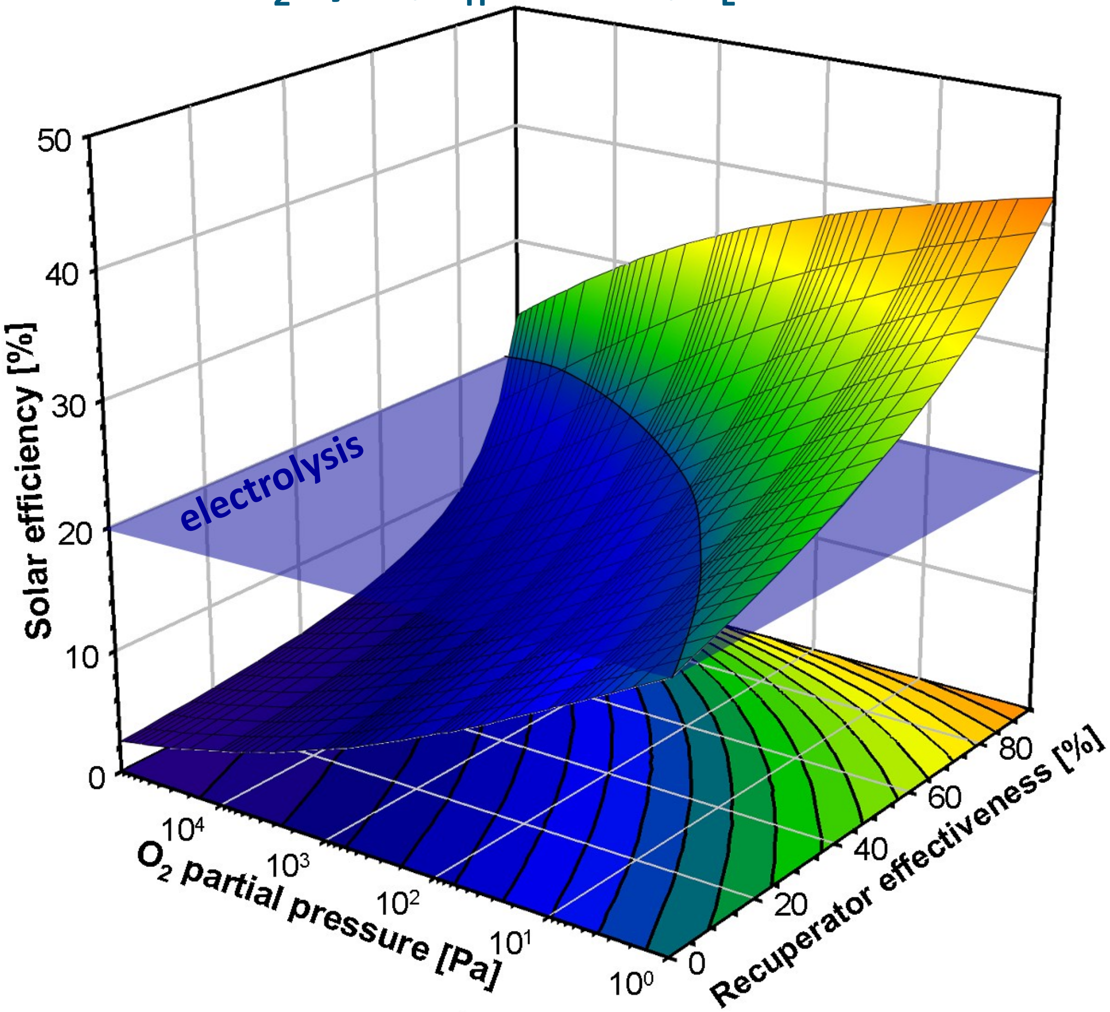


$$CeO_2 \rightarrow CeO_{2-\delta} + \frac{\delta}{2} O_2$$

$$CeO_{2-\delta} + \delta \cdot H_2O \rightarrow CeO_2 + \delta \cdot H_2$$

High Solar Efficiency: Key Parameters

CeO_2 cycle, T_H=1500°C, T_L=1100°C



- Solar→H_2 efficiency >30% possible with CeO_2
- 75% Heat recovery required

All-inclusive efficiency metric:

- Collection losses
  - Concentrator & re-radiation
- Oxide heating
- Oxide thermal reduction
- Feedstock heating (steam)
- Pumping
- Electrical/mechanical work

$$\eta = \frac{\dot{n}_{H_2} \cdot HHV_{H_2}}{P_S}$$

Challenges:

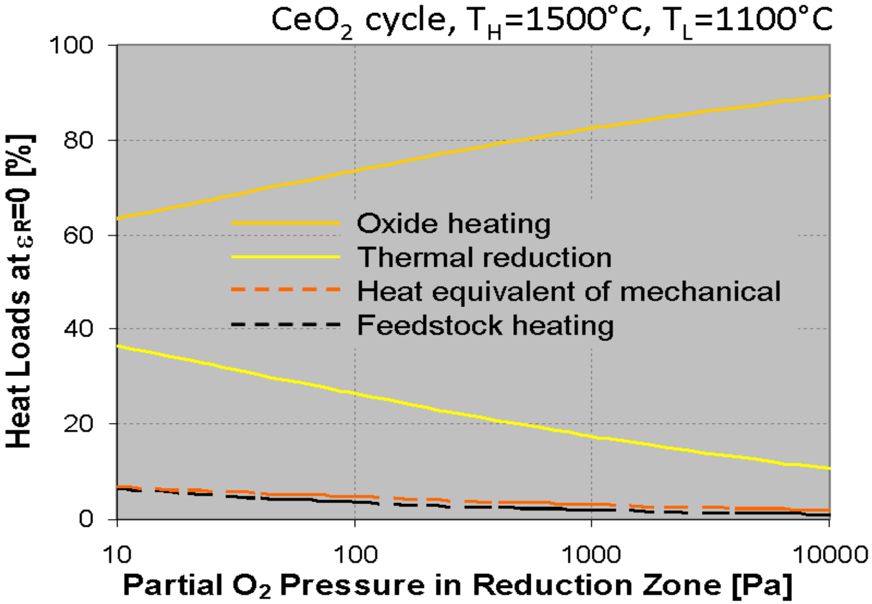
- **High counter-flow heat recovery**
- **Low p_{O2} for reduction**

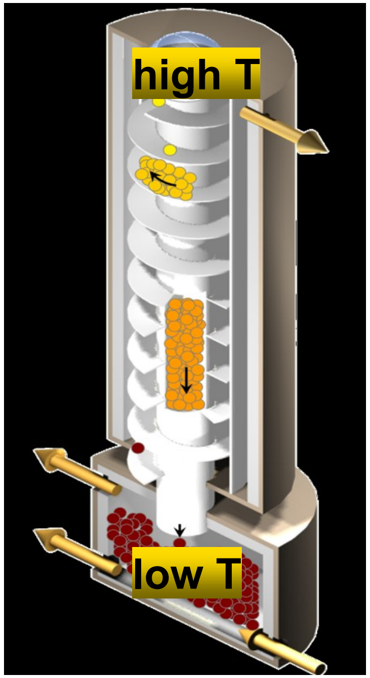
Approach:

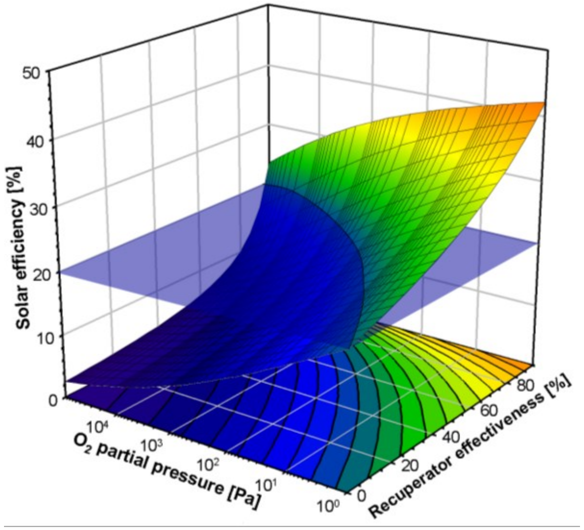
- **Recuperator design and testing**
- **Reactor design**
- **Reactive oxide design**

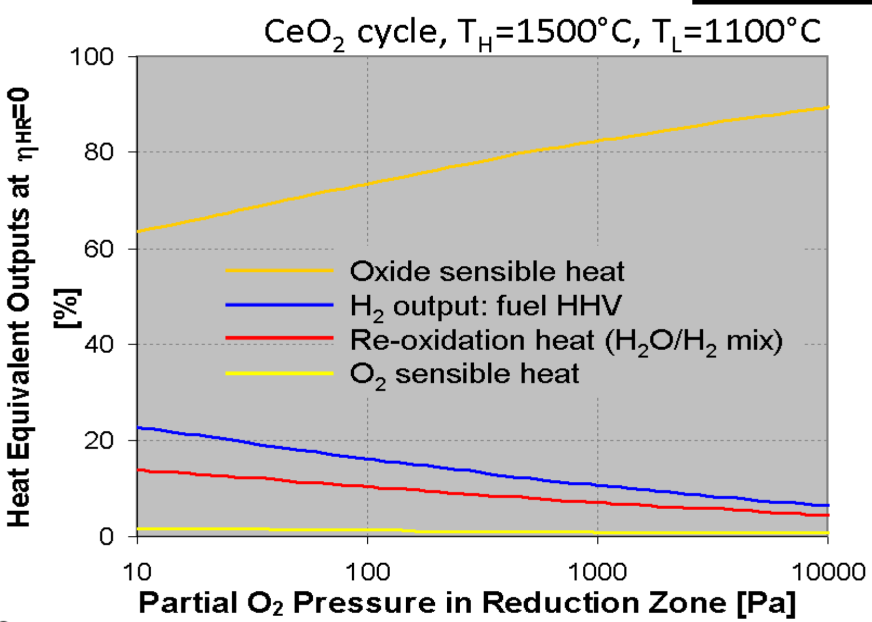
Recuperator Effectiveness: Critical Importance

Heat flows without heat recovery









- **Not recovering heat is NOT an option**
- **75% minimum with CeO_2**

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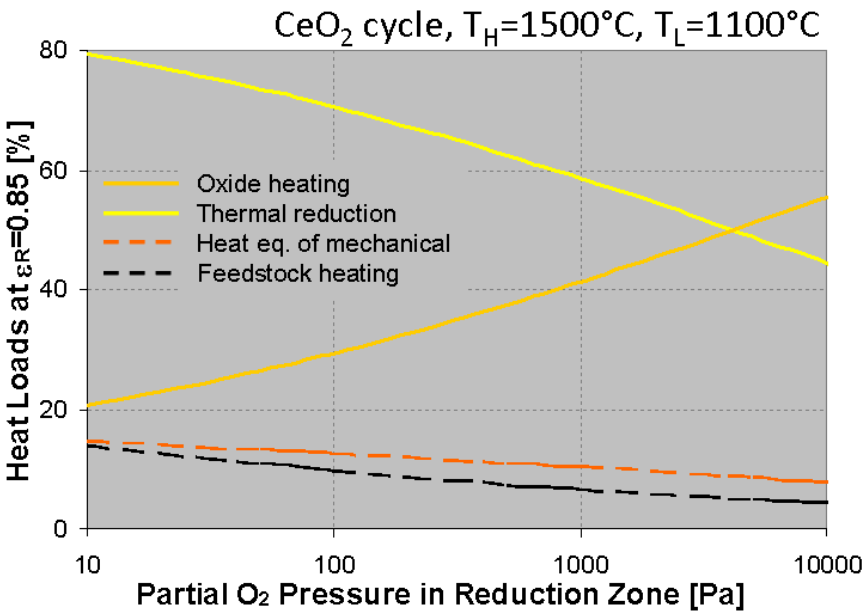
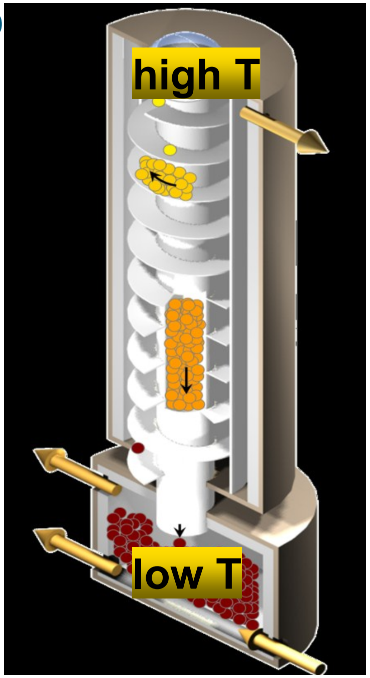
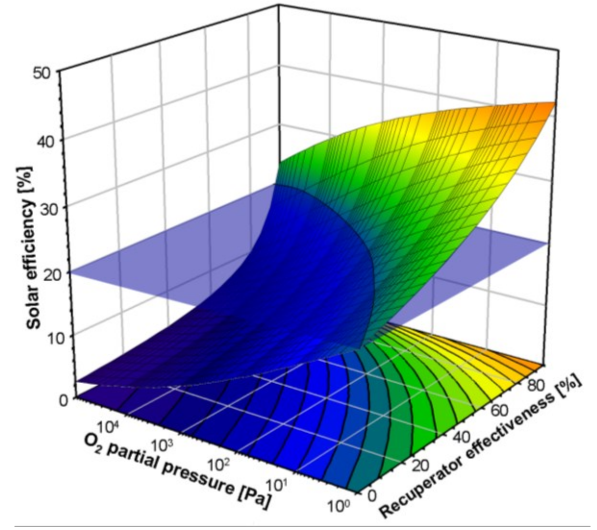
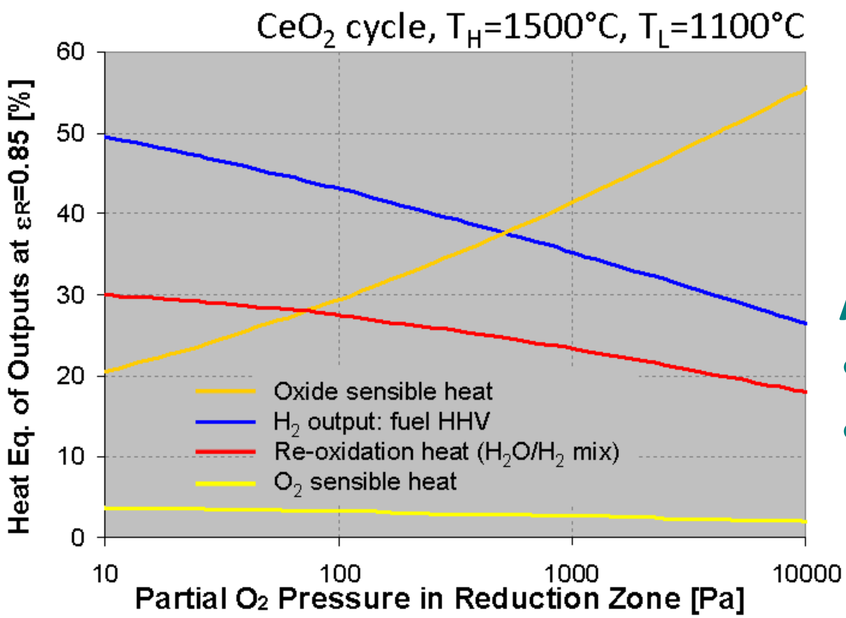
Recuperator Effectiveness: Critical Importance

Heat flows with 85% solid-solid heat reco









Challenge: Conveyor-Recuperator design must convey active oxide particles *and* recover heat

Approach:

- **Recuperator numerical modeling**
- **Design, construction, and testing under increasingly realistic conditions**

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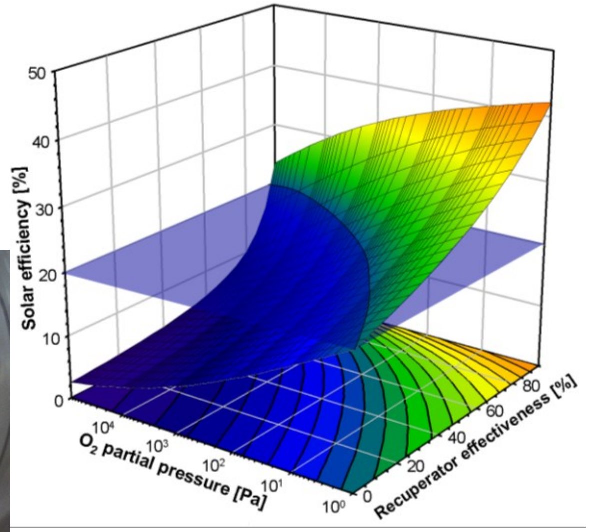
Recuperator Effectiveness: Conveyor Design

- Highly modified elevator design
- Internal fins used for enhanced heat recovery
- Use multiple auger design to increase heat recovery



- Multi-helix design shows the most promise so far

Challenges:

- Evaluate and develop the nested multi-screw design
- Build prototypes to assess conveyor-recuperator effectiveness
- Determine the conveyor-recuperator manufacturing approaches at various scales and establish reactor size limits

Approach:

- Construction and testing of multiple units
- Use of surrogate materials as well as CeO_2

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Prototype Platform Design and Construction

- Highly modified elevator design
- Internal fins used for enhanced heat recovery
- Use multiple auger design to increase heat recovery

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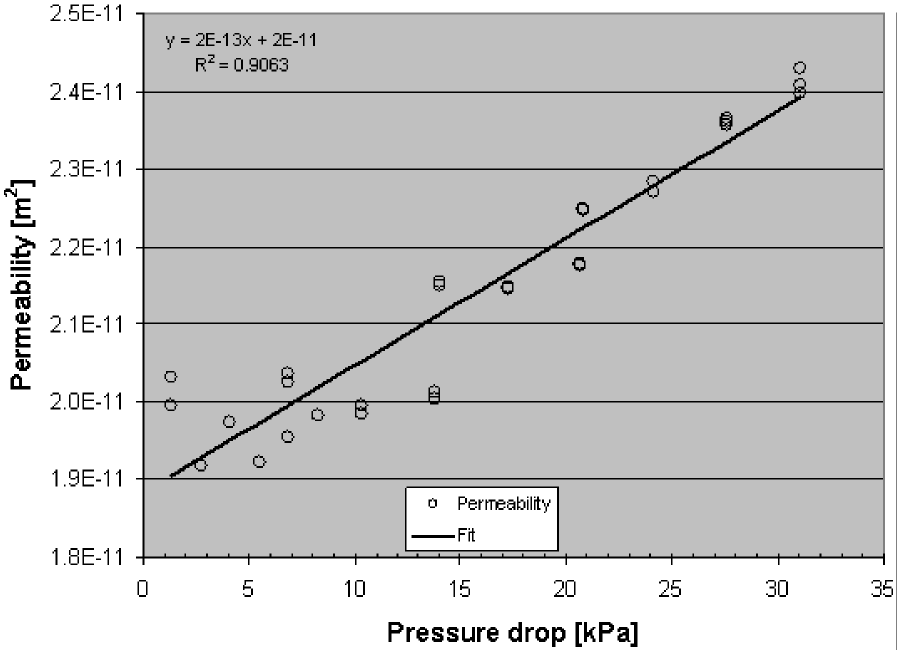
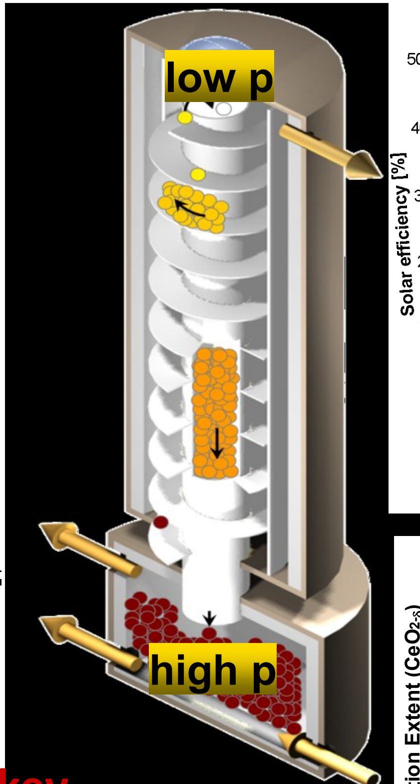
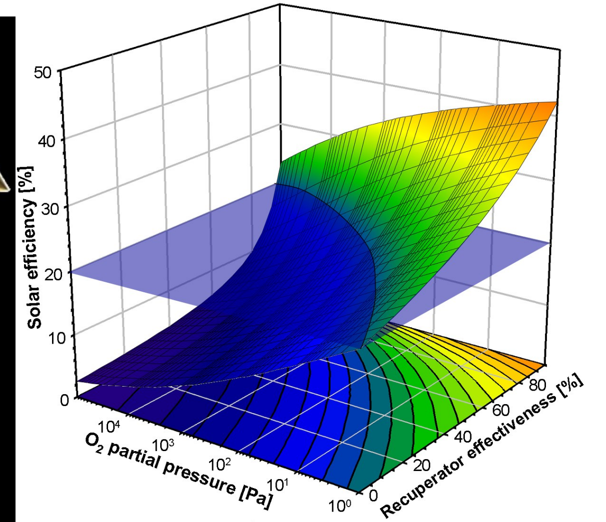
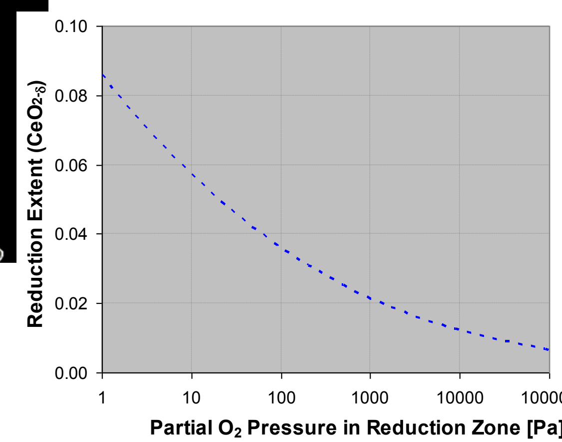
Decreasing O_2 Partial Pressure: Particle Design









Preliminary permeability measurements of surrogate zirconia-silica microspheres

Low gas permeability of the oxide bed is key to pressure separation and high efficiency

Challenge: "Marry" the particles and Δp requirements

Approach:

- **Determine the optimal particle size range**
- **Develop and scale up a synthesis method**
- **Test chemical and mechanical durability**

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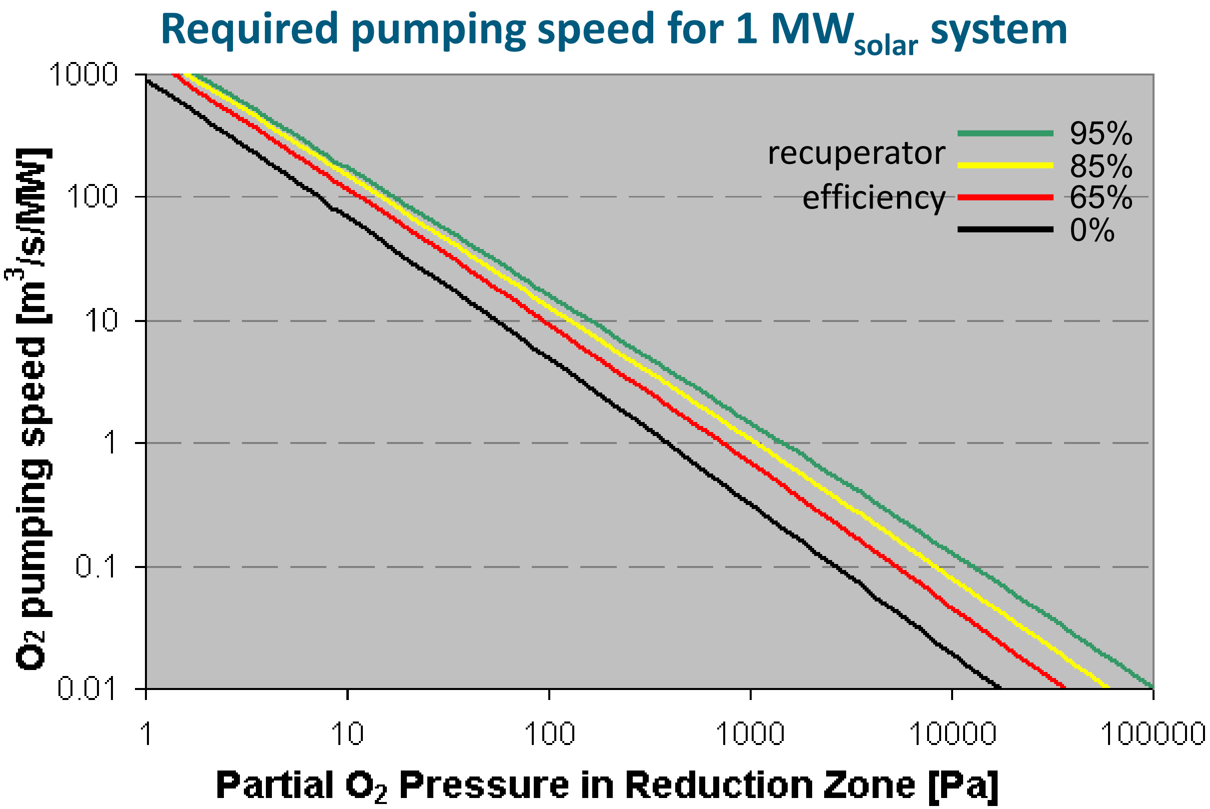
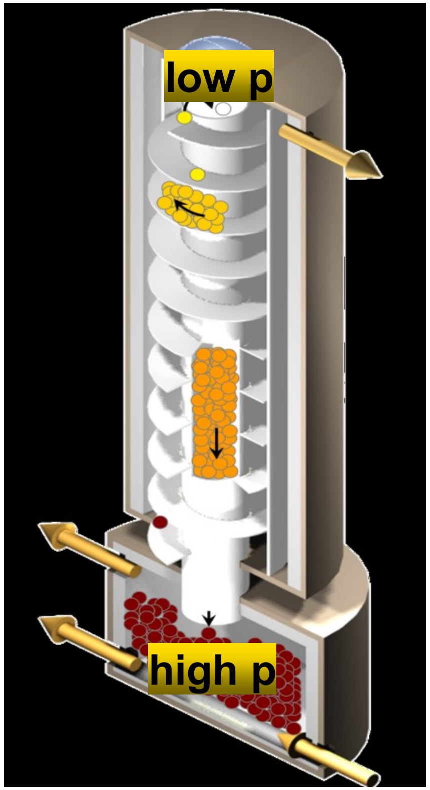
Decreasing O_2 Partial Pressure: Pumping Limits





Pumping requirements establish limits to reactor size and pressure

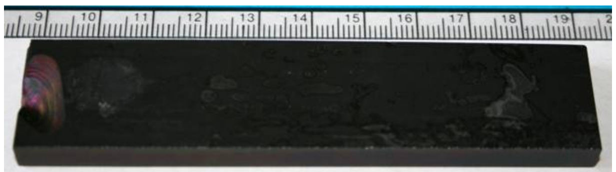
Challenge: Select or develop efficient compressors suited for the application (compression ratio ~100-1000, inlet flow ~10-1000 m^3/s)

Approach:

- **Use the most suitable off-the-shelf pumps**
- **Evaluate scale-up feasibility with turbomachinery manufacturers**

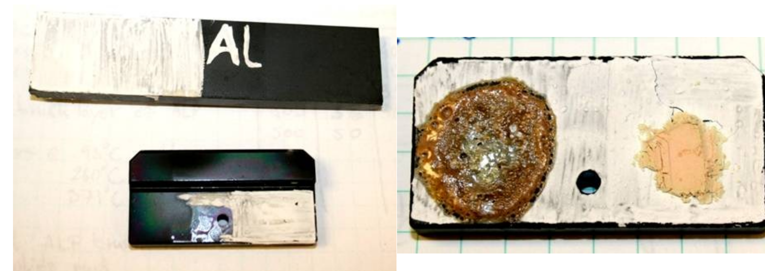
Reactor Materials

- Reactor parts and reactive oxide <u>must not</u> react, even at T_H
- Multiple materials tested under realistic conditions
- Alumina compatible to 1550°C, SiC to 1400°C, alumina-coated SiC to 1450°C
- Identified potential ceramic component manufacturer



CeO_2/SiC Hexoloy, 1400°C
stagnant air, 3h

CeO_2/Al_2O_3, 1550°C
stagnant air, 3h



paint CeO_2/Al_2O_3/SiC, 1450°C
stagnant air, 3h

- For CeO2 reactive oxide no manufacturing showstoppers expected

Challenges:

- Compatibility with every active oxide is required

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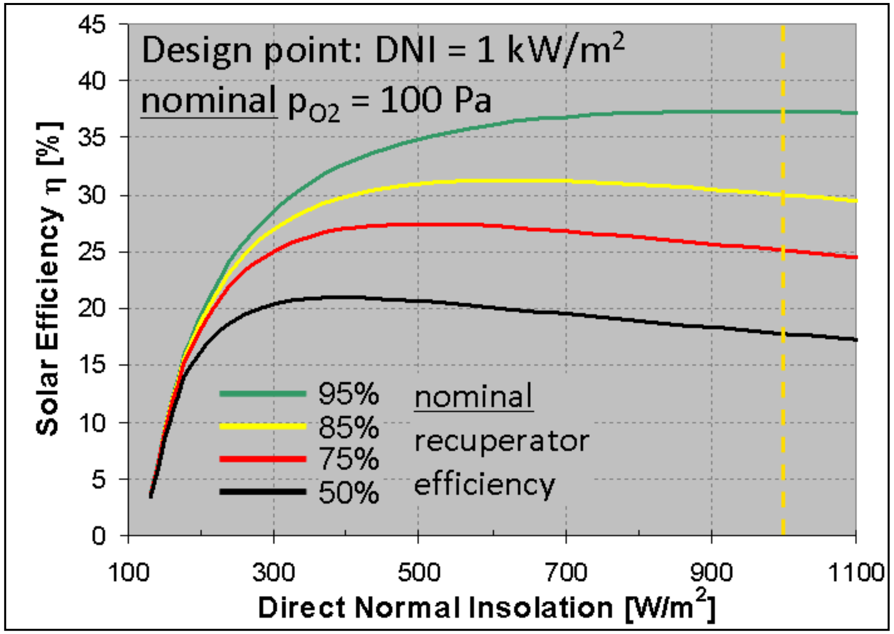
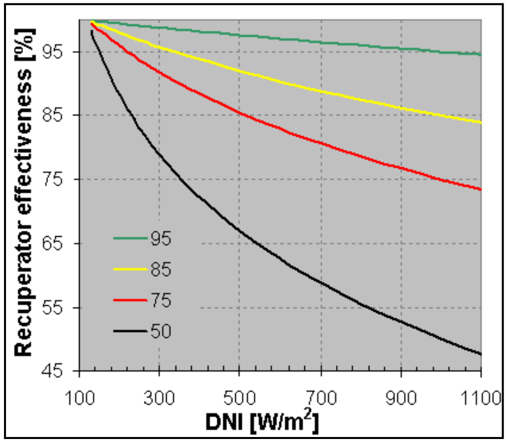
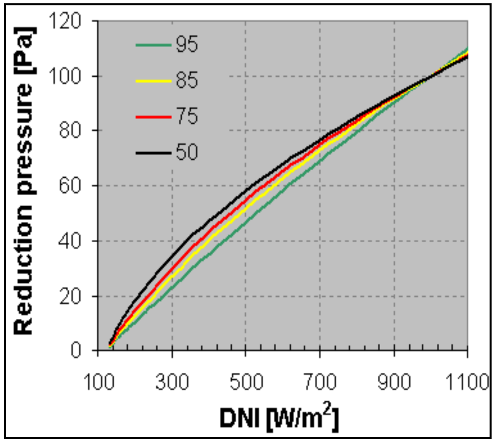
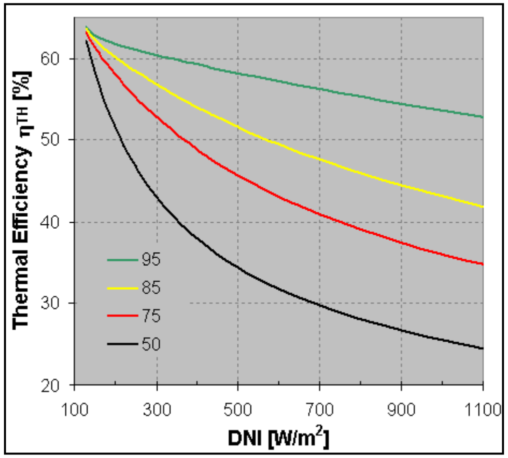
Operational Flexibility →High Annual Average Efficiency

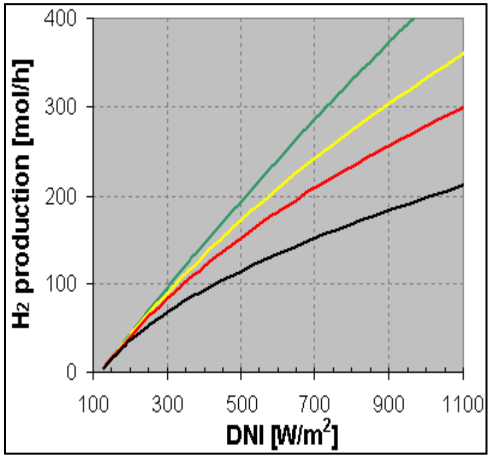


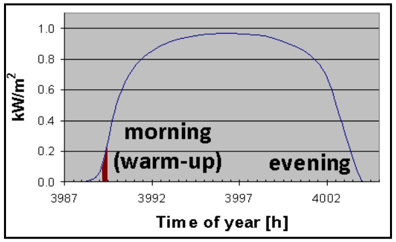


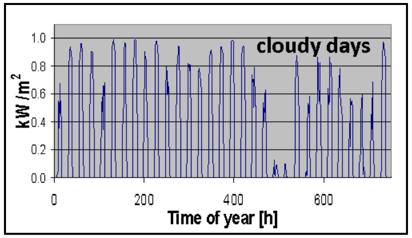


Low DNI → Increased heat recovery & Decreased p_{O2} → High efficiency









- High solar utilization for most conditions
- 25% solar-to-H2 annual efficiency expected
- Use of low DNI for system warm-up

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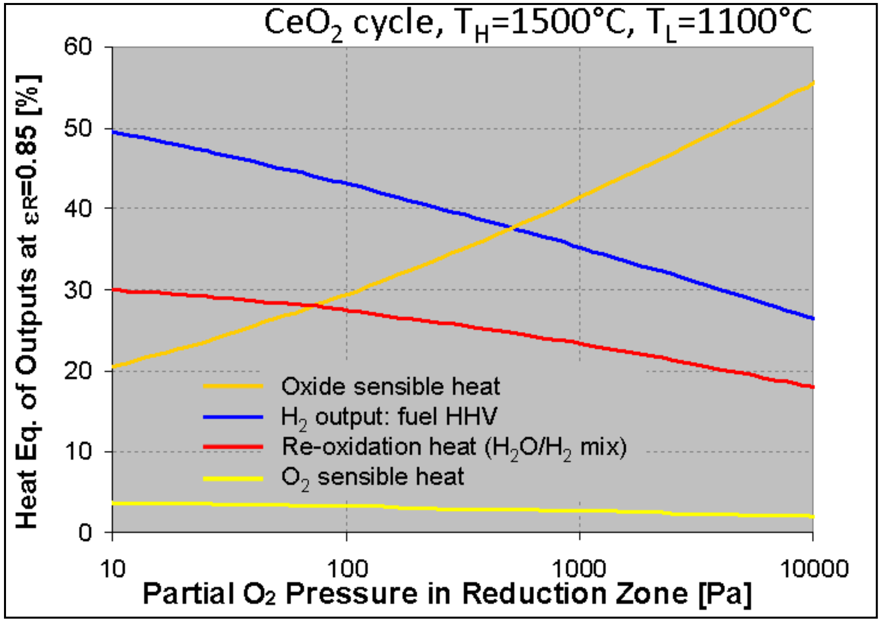
Challenge: Long term operation and evaluation under a variety of realistic conditions

Other Issues: 1-3 slides



- **Reoxidation waste heat is high for CeO_2**

Challenge: Discover a second generation of redox active materials with decreased ΔH and T_H

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Back to the Big Picture: 5-10 year vision

Thank you for your attention

Questions?

System Level: Many Losses and High Annual Efficiency

Resource efficiency = 95% for Daggett, CA (DNI > 300W/m^2)

Operational ~ 94%

Equip. Availability = 97%, Blocking&Shading = 98%, Wind Outage = 99%

Optical ~ 79%

Reflectivity = 93% (two reflections)

Dirt = 95%

Window = 95%

Tracking = 99%

Intercept = 95%

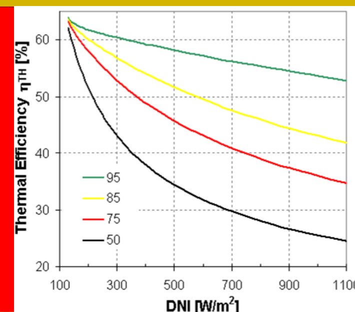
Receiver ~ 82%

Radiation = 82%

Conduction/Convection = 0 %

Solar-to heat: ~58%

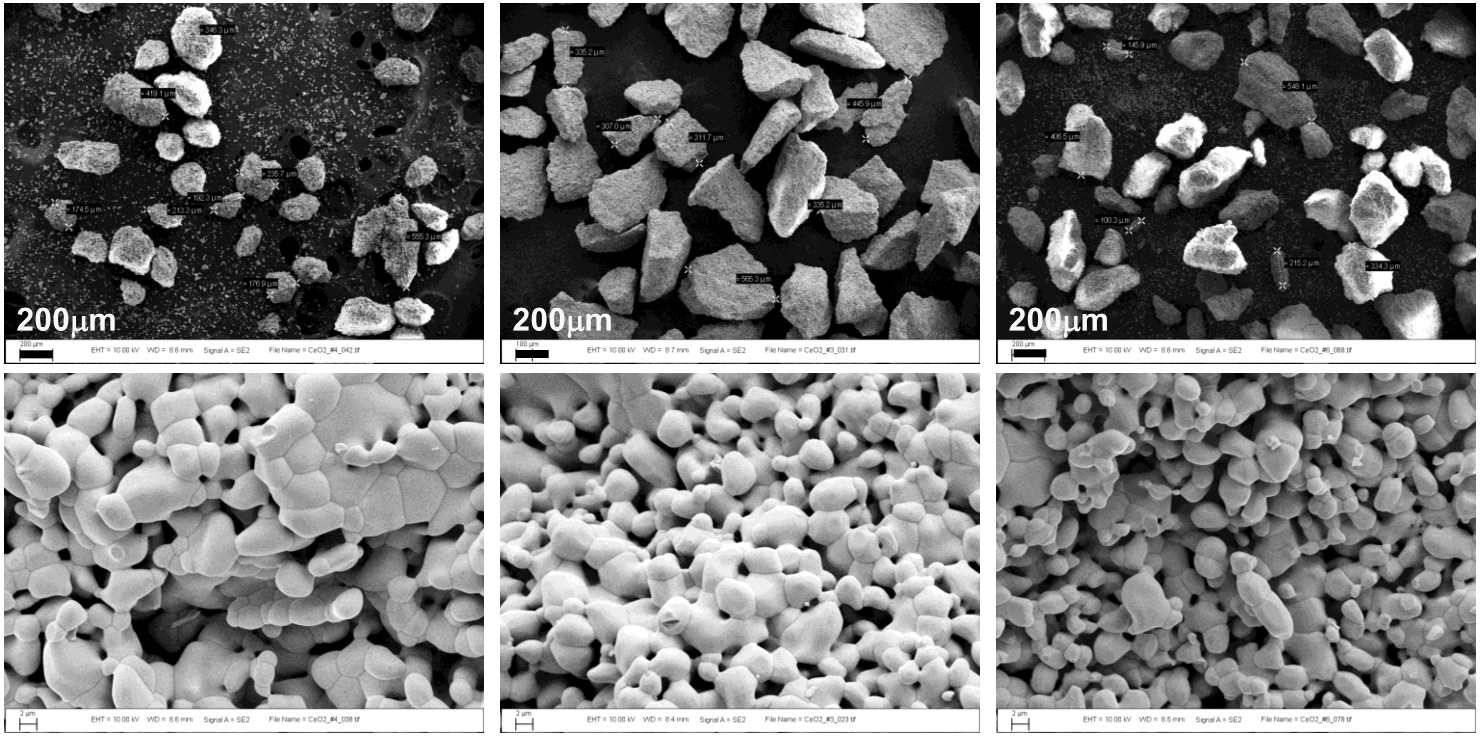
Thermal ~44%

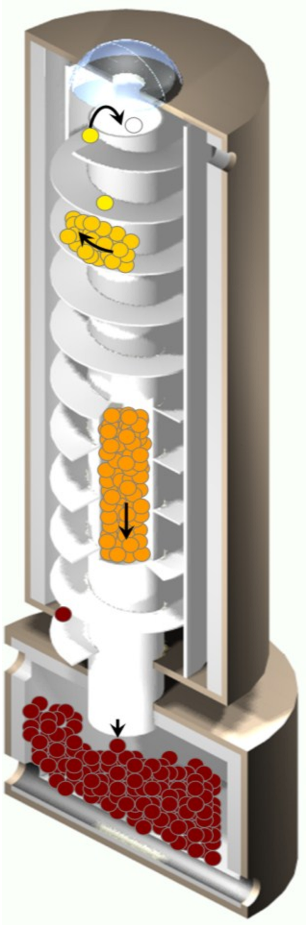


~25% solar to H_2 annual average

Recuperator Effectiveness: Particle Design

Ceria particles synthesized from 5μm powder





Conveying efficiency depends strongly on particle shape, size, density, cohesive strength, etc. – in addition to conveyor design.

Challenge: "Marry" the particles and the conveyor

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Approach:

- Determine the optimal particle size range
- Develop and scale up a synthesis method
- Test chemical and mechanical durability

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