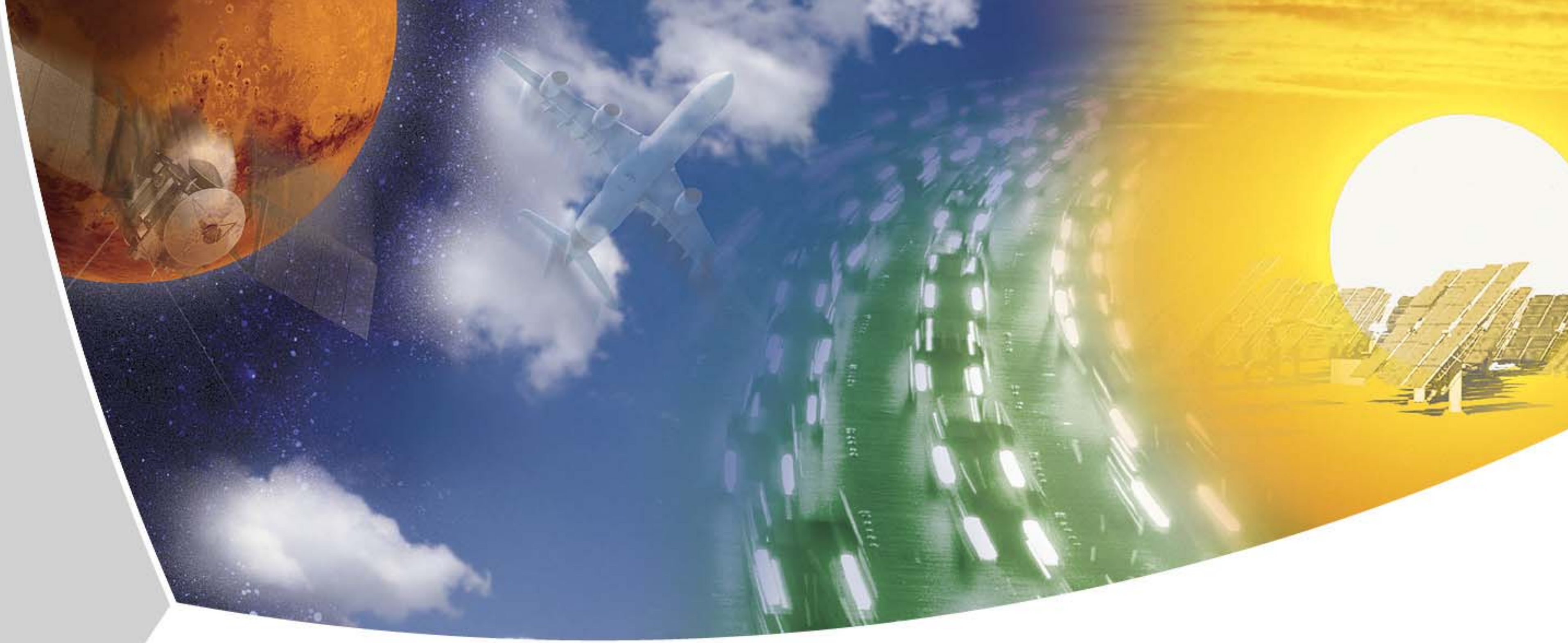

Solar Thermal Fuel Production at DLR

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DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Conversion of Solar Energy into Solar Fuels

Direct =

Heat

Thermochemical process mainly for the production of syngas and hydrogen

Photoelectrochemical processes for the generation of fuels e.g. hydrogen, hydrocarbons, and alcohols

Indirect =

Heat + Electricity

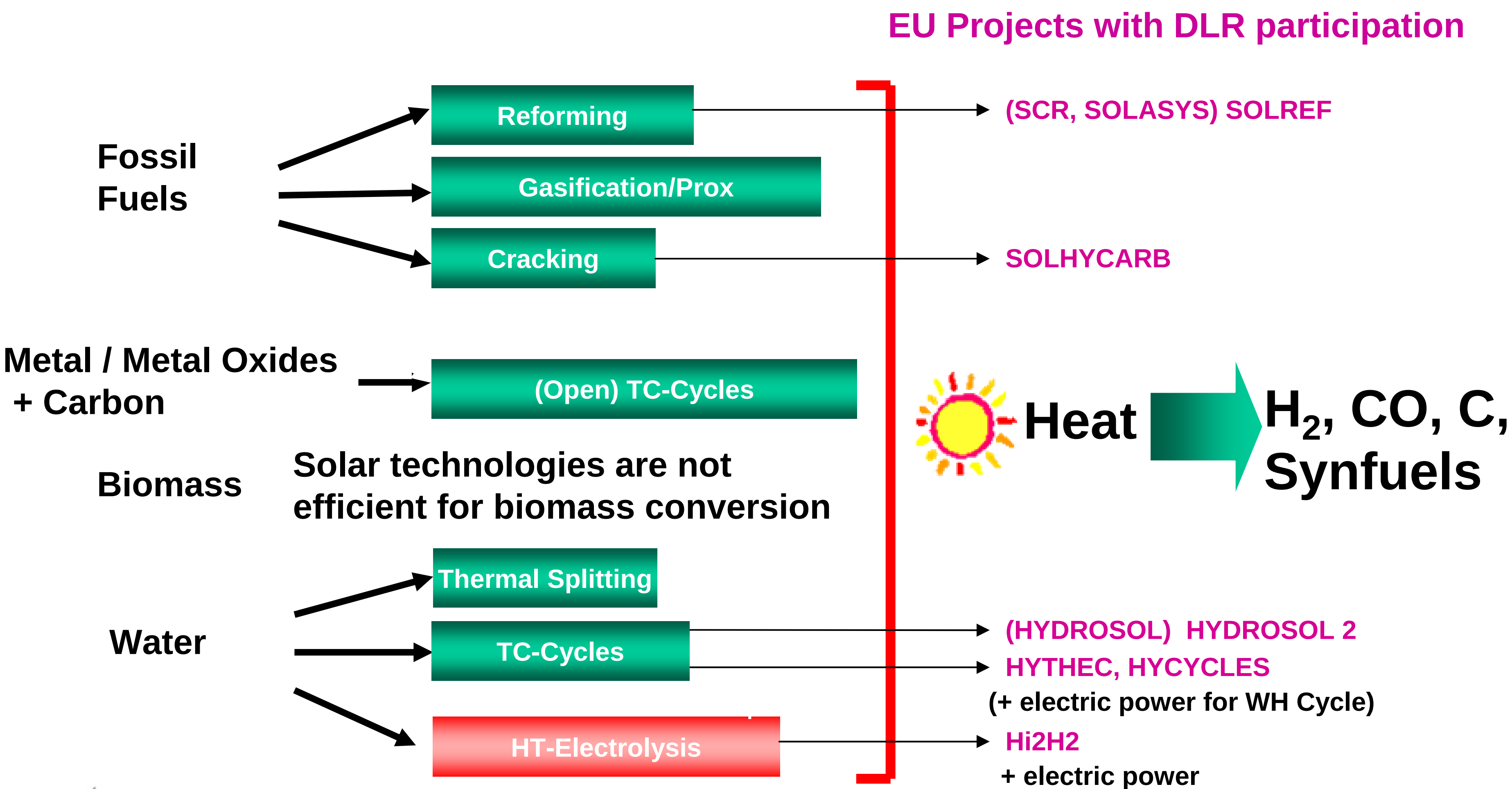
Power generation

Hydrogen production by electrolysis

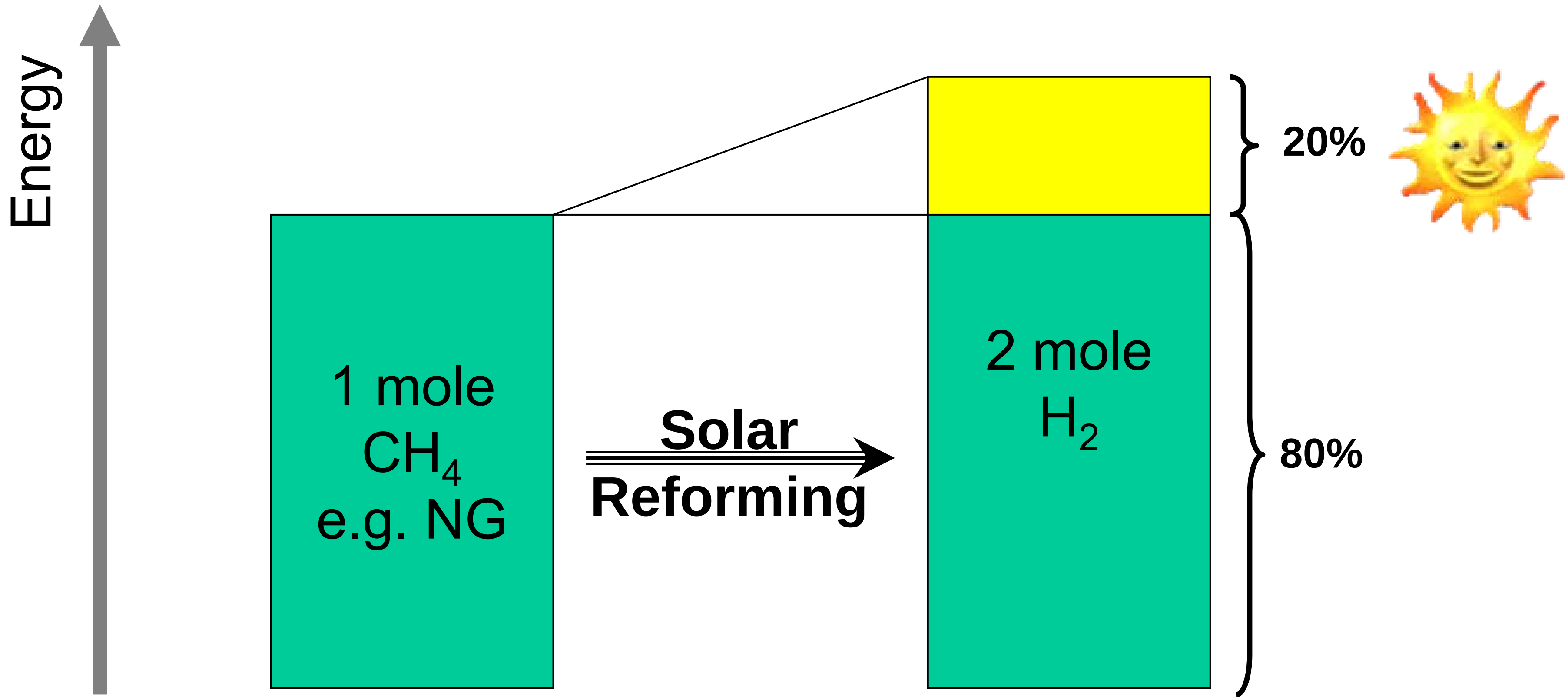
Criteria for the Selection of Suitable Processes for Solar Thermal Fuel Production

- Environmentally benign and safe process.
- Technically feasible operation temperature, concentration factor, materials, reaction, throughput.
- High availability of feed-stock.
- Fast reactions with short residence time are preferable.
- High overall process efficiency.
- Fuel must be produced at acceptable cost

Solar Thermal Fuel Production Routes

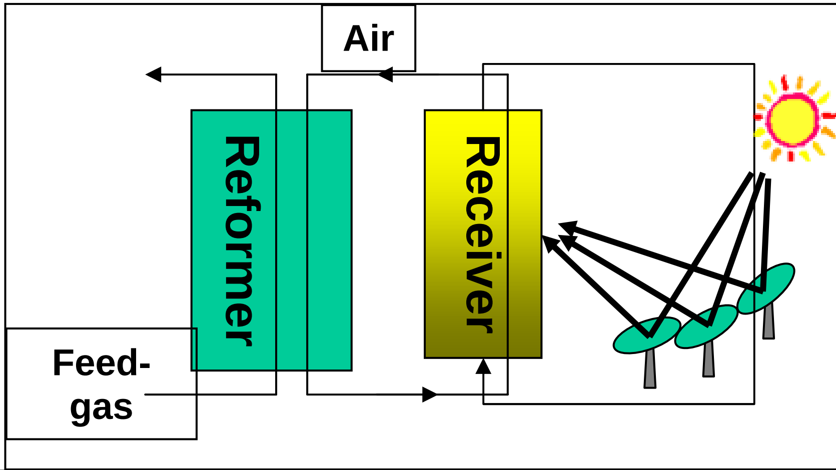


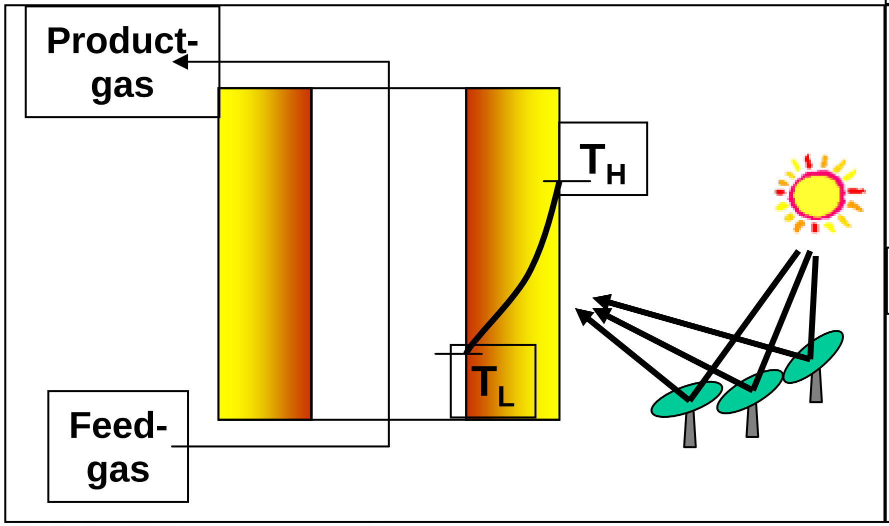
Partly-Solar Hydrogen

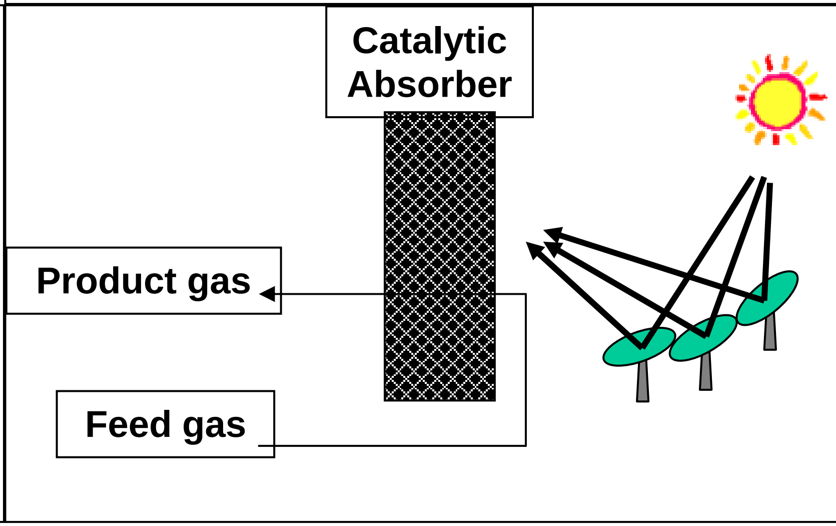


Solar Steam Reforming of Natural Gas

- **External: ASTERIX**
- **Indirect: MUSTR, CSIRO**
- **Direct: SCR, SOLASYS, <u>SOLREF</u>**
  - FP 6 Project
  - Enhanced Receiver + Demo Model
  - Partner DLR, WIS, ETH/PSI, JM, SHAP, HyGear, CERTH/CPERI







Experimental Results SOLASYS (EU FP4)

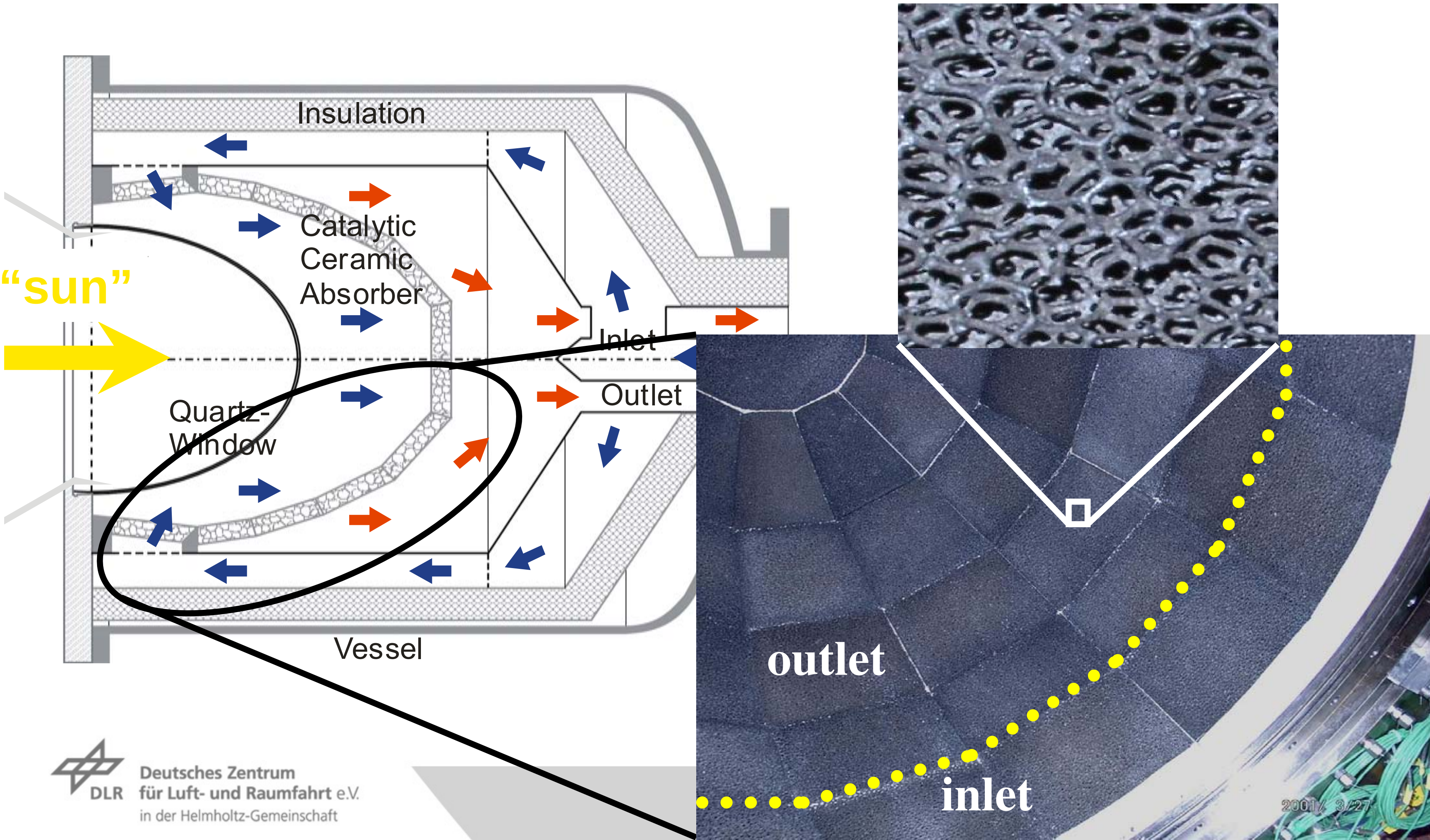
- Solar power input: 100 - 220 kW_{th}
- Reforming temperature: 700 - 765°C
- Pressure: 4 - 9 bar
- Conversion of Methane: max. 78 %
- Corresponds with the theoretical equilibrium.

3 MW_{th} Solar Tower, WIS, Rehovot, Israel

Development of Receiver/Reactor

- Develop an advanced catalytically-active absorber featuring the following properties:
  - High catalytic activity with high resistance to coking.
  - Good absorption for thermal radiation.
  - Acceptable mechanical strength and thermal shock resistance.
  - High gas permeability together with high turbulence and mixing of the gases as well as low pressure drop.
  - Low costs.

Schematic of Solar Reformer

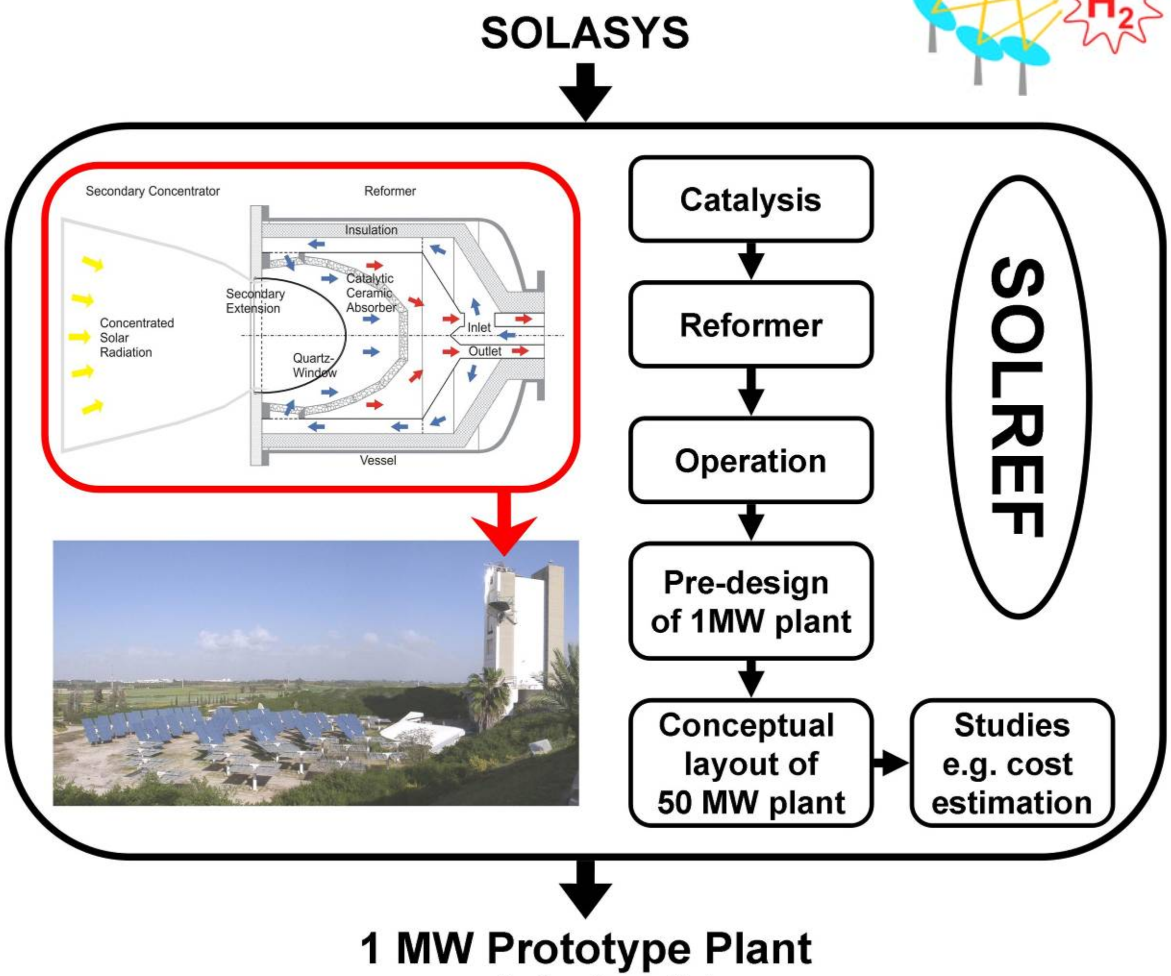


Solar Steam Reforming of Natural Gas - SOLREF

2004 – 2008

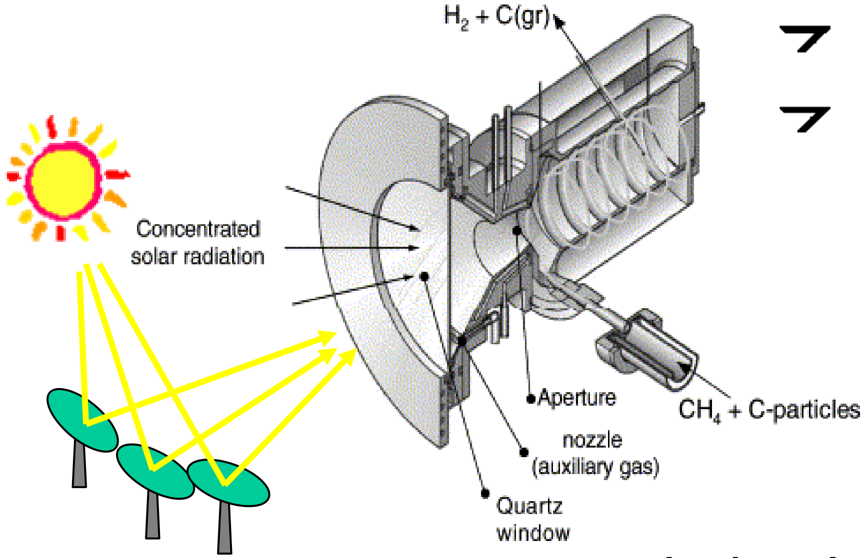
Consortium:

- DLR (DE) (Coordinator)
- CERTH/CPERI (EL)
- WIS (IL)
- ETH (CH)
- Johnson Matthey Fuel Cell Ltd. (UK)
- HyGear B.V. (NL)
- SHAP S.p.A. (I)

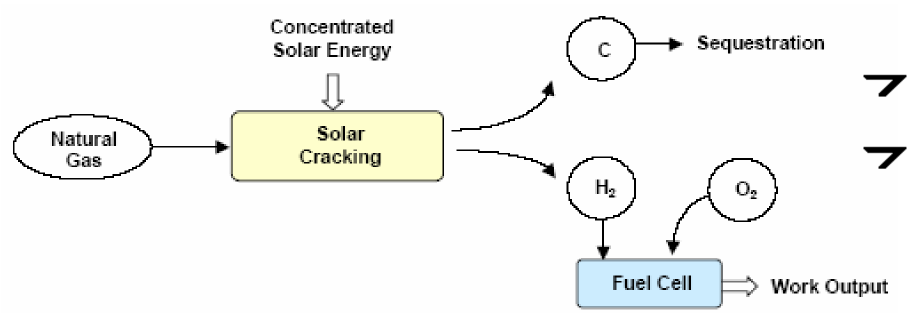


Location North Africa?

H_2-Production by Solar Cracking of Hydrocarbons



Source: Hirsch et al.



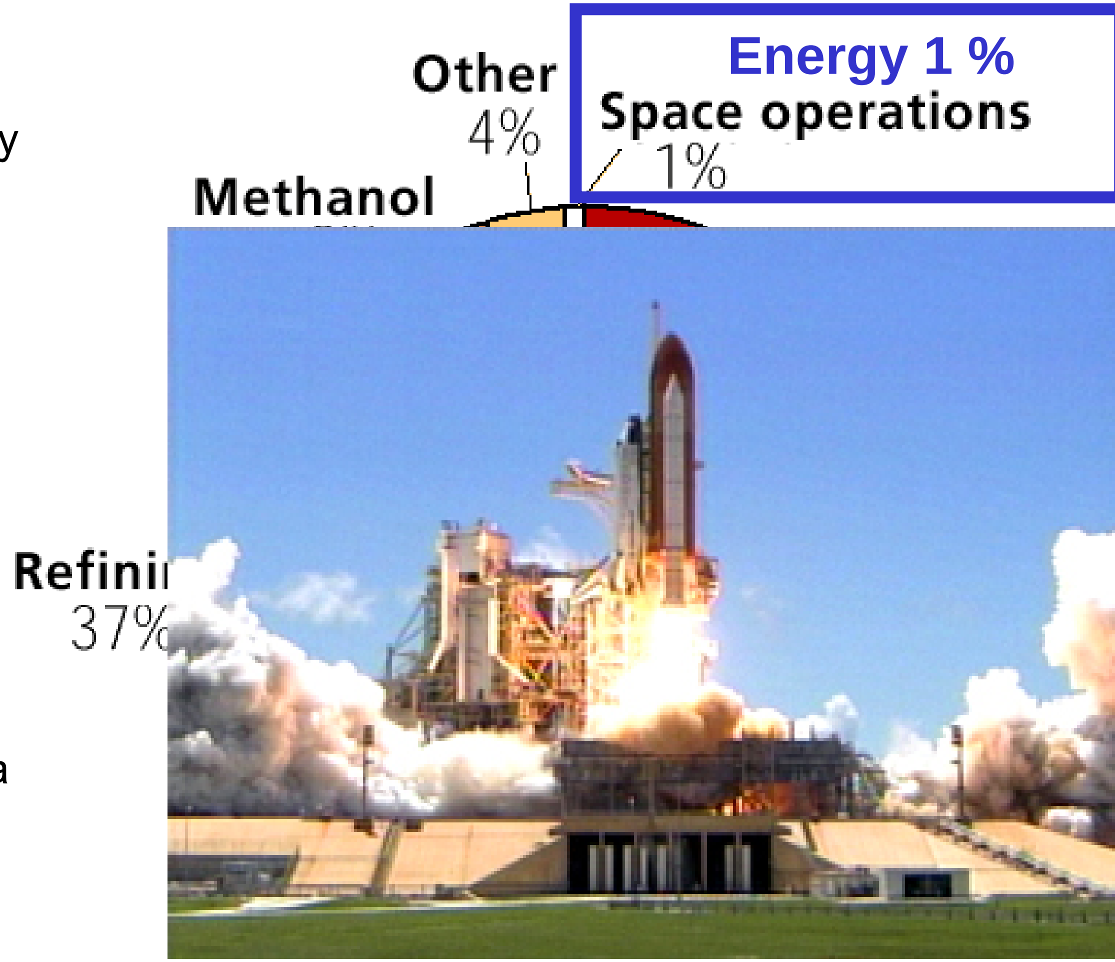
- Work done by ETH, PSI, CNRS, WIS …
- Decarbonisation of Methane

  $CH_4 \leftrightarrow C + 2H_2$

  - Temperature > 1300°C
  - Ambient pressure.
  - Conversion rate 70%.
  - Theoratical system efficiency: 30%
  - Cost: 8 ct/kWh [Dahl et al.]
    (0-14 ct/kWh depending on the use of the carbon)
  - EU Project SOLHYCARB since March 2006
  - Partner CNRS/PROMES (FR) - Coordinator, ETH, PSI (CH), WIS (IL), CERTH/CPERI (EL), DLR (DE), TIMCAL (BE), SOLUCAR (SP), CREED (FR), N-GHY (FR)

Solar, Carbon-Free Hydrogen Production

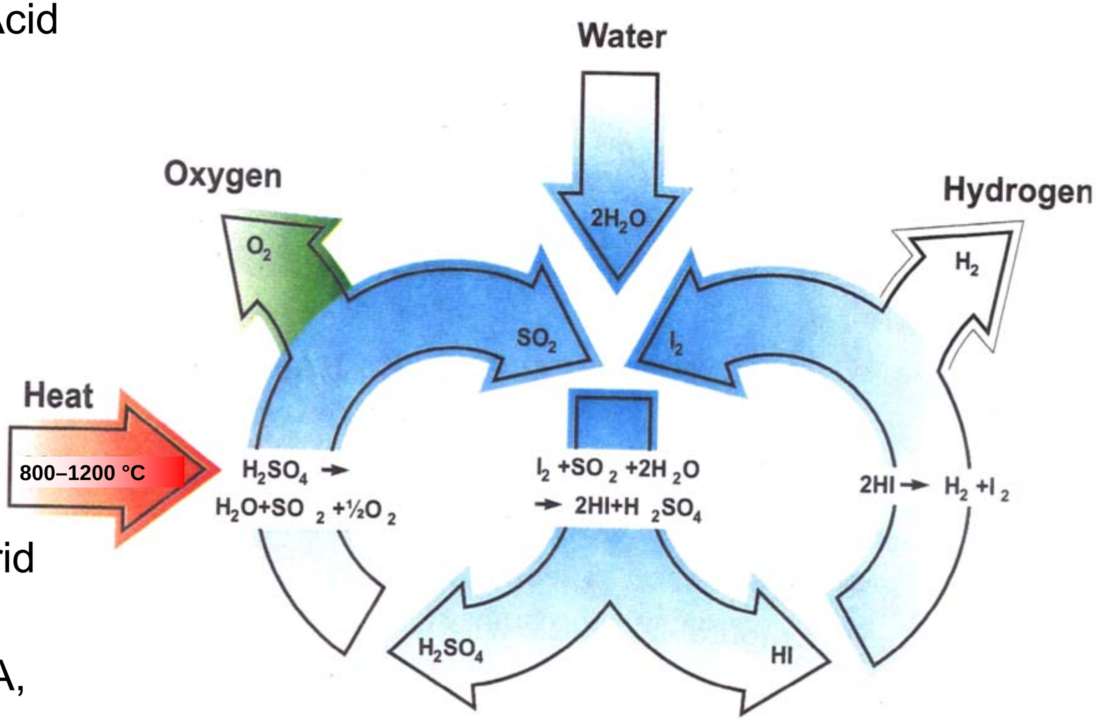
- Today, hydrogen is still a bulk chemical rather than an energy vector
- Annual production:
  600 – 700 billion Nm^3/year
  equal to 53 – 62 Mt/year
- Virtual value
  100 billion €/year
- Growth rate about
  10 %/year (2003, Linde)
- Only 4 % traded commercially
- Ammonia production alone generates about 250 Mt CO_2/a



Solar, Carbon-Free Hydrogen Production

HYTHEC - Sulphur/Iodine and Hybrid Sulfuric Acid Cycle

- Also named General Atomics Cycle or ISPRA Mark 16 and Hybrid Sulfuric Acid Cycle also known as Westinghouse Cycle or ISPRA Mark 11
- EU FP6 STREP HYTHEC
- Solarisation of H_2SO_4 splitting
- Improvement of processes and increase of efficiency
- Design study for a H_2/Elctricity Co-generation plant
- Evaluation of solar, nuclear, and hybrid concepts
- Partners: CEA (coordinator), DLR, EA, Uni Sheffield, Uni Roma Tre, ProSim

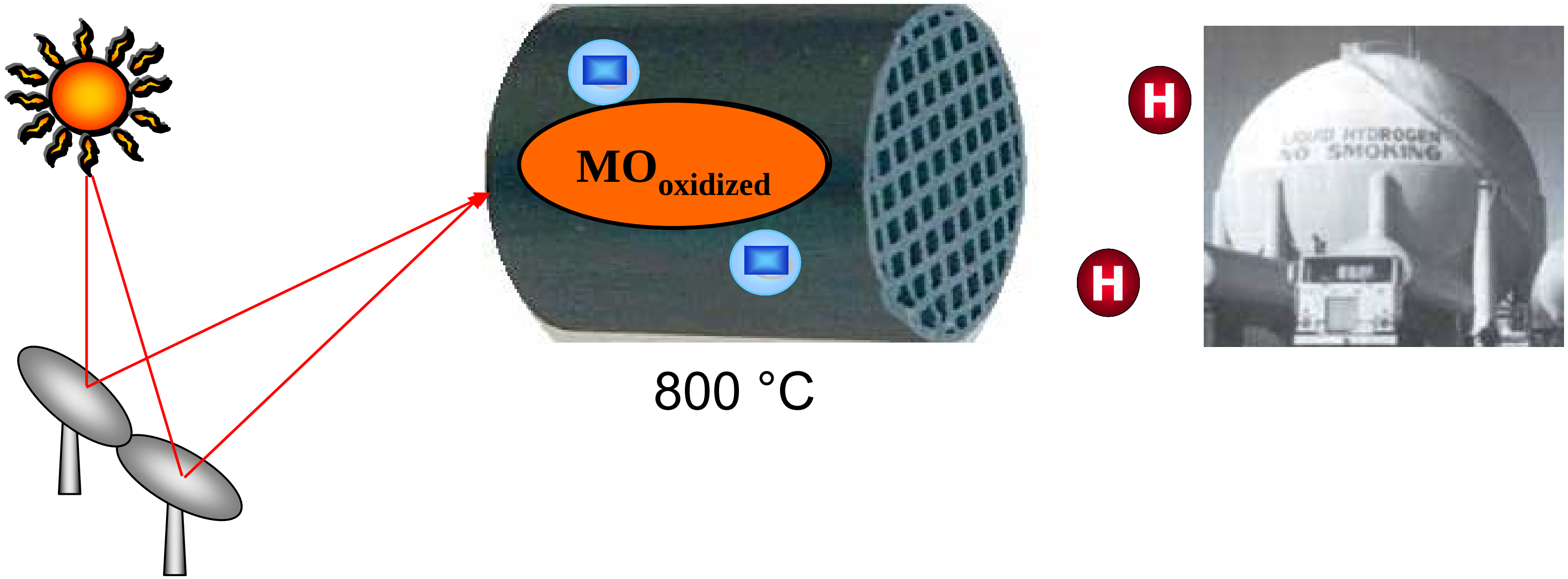


[ORNL]

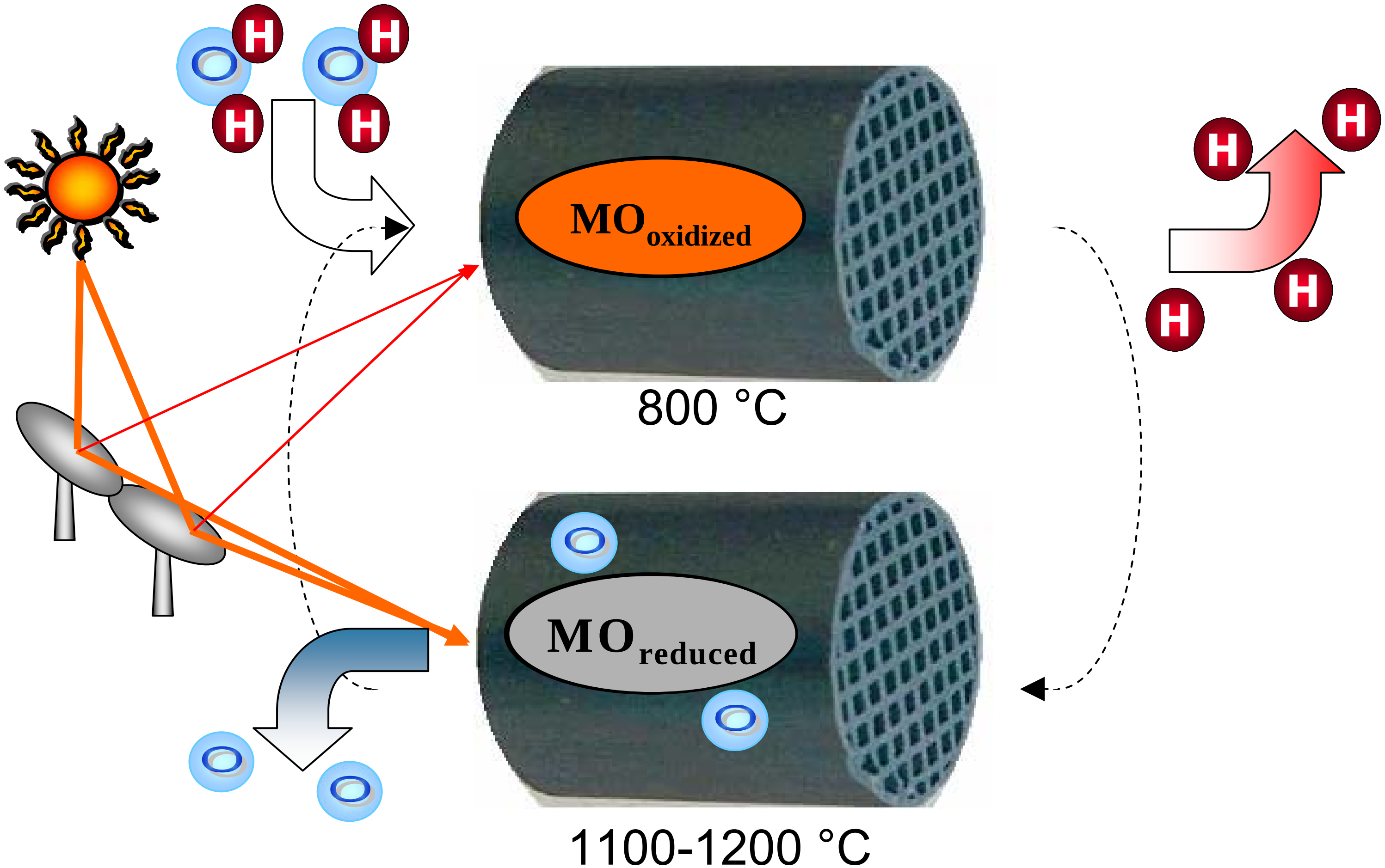
HYDROSOL: MONOLITH REACTOR FOR HYDROGEN GENERATION FROM SOLAR WATER SPLITTING

- STREP EU FP 5 (Nov. 2002 – Oct. 2005)
- Consortium: CERTH/CPERI APTL (EL, Coordinator), DLR (D), Johnson Matthey Fuel Cell Ltd. (UK), StobbeTech (DK)
- Objectives:
  - Development of novel active redox materials for the water splitting and regeneration reactions at moderate temperatures (800-1300 °C).
  - Design, construction, and test operation of a prototype reactor for continuous hydrogen generation based on a thermochemical cycle applying mixed iron oxides
  - Feasibility of operability of solar thermal two-step hydrogen production
  - Evaluation of techno-economic potential of the technology

HYDROSOL – Principle of Operation



HYDROSOL – Principle of Operation



Batch-Reaktor after completion

Coated absorber

DLR Solar Furnace, Köln-Porz

Operation started in 1994

Off-axis Concept

Heliostat 60 m^2

Concentrator 39 m^2

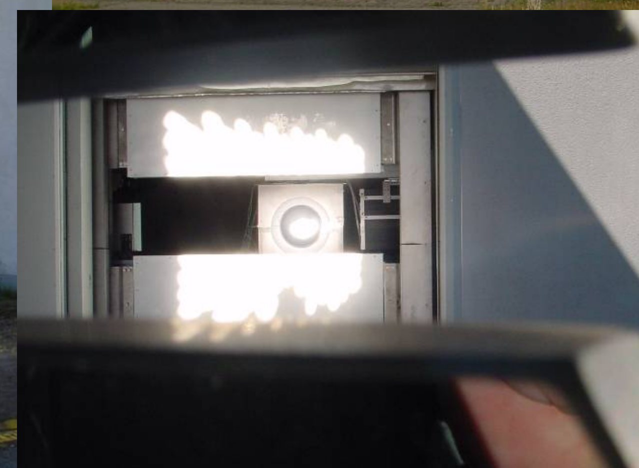
160 Facettes, 3 Focal lengths

Concentration: 5500 = 5 MW/m^2

Power max. 25 kW

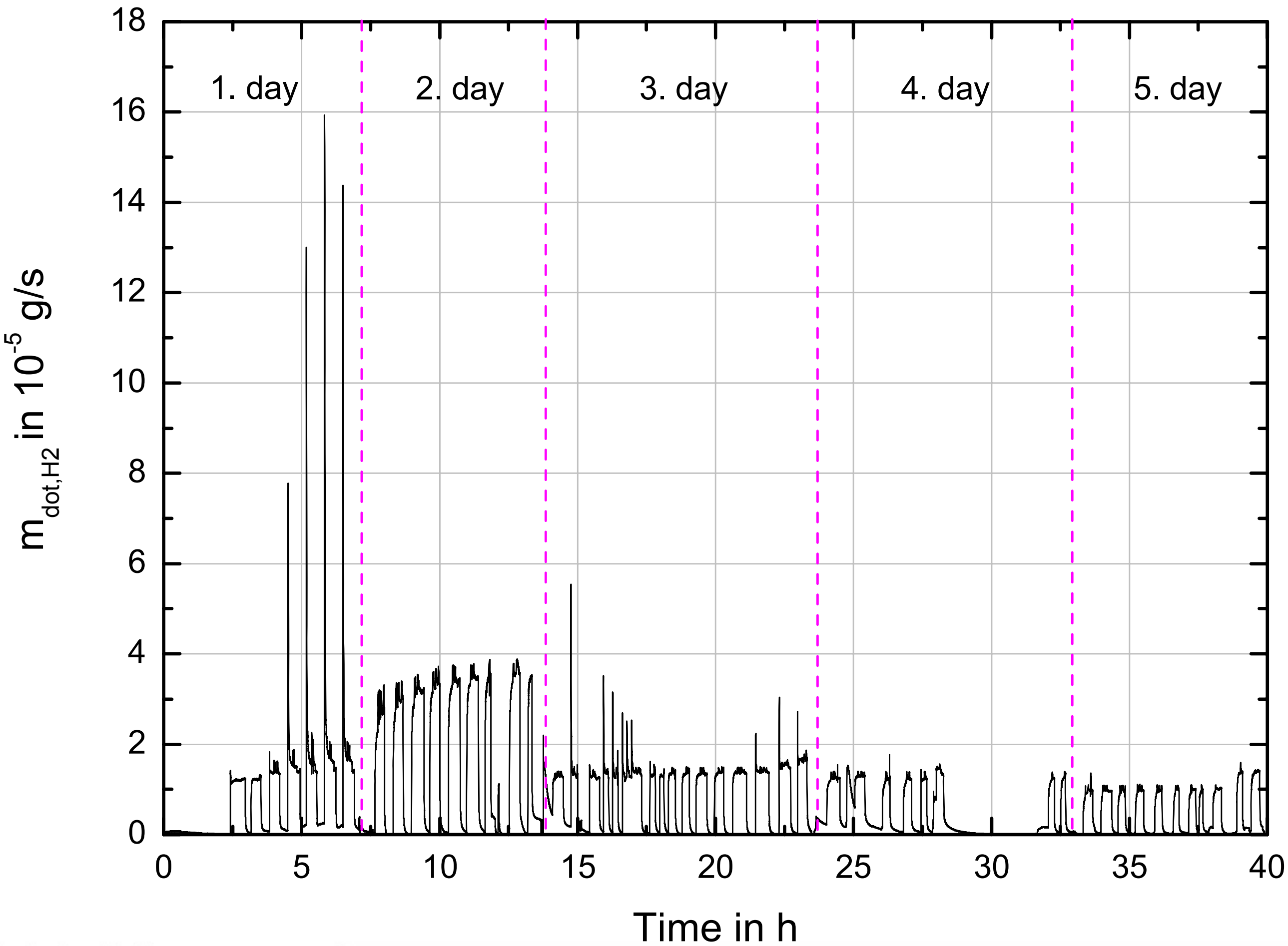
Focus 13 cm (90%)

T_{max} 2700 °C



Long-term test

Hydrogen generation for 53 cycles performed with one sample



Efficiency and characteristics of operation

- stability of the redox/support-composite proved up to **40 cycles of constant H_2 production**
- quasi-continuously hydrogen generation / alternating reaction conditions
- SiC and in particular SiSiC turned out as very suitable, robust support material
- Reaction controlled by kinetics

Efficiency of the solar furnace operation:

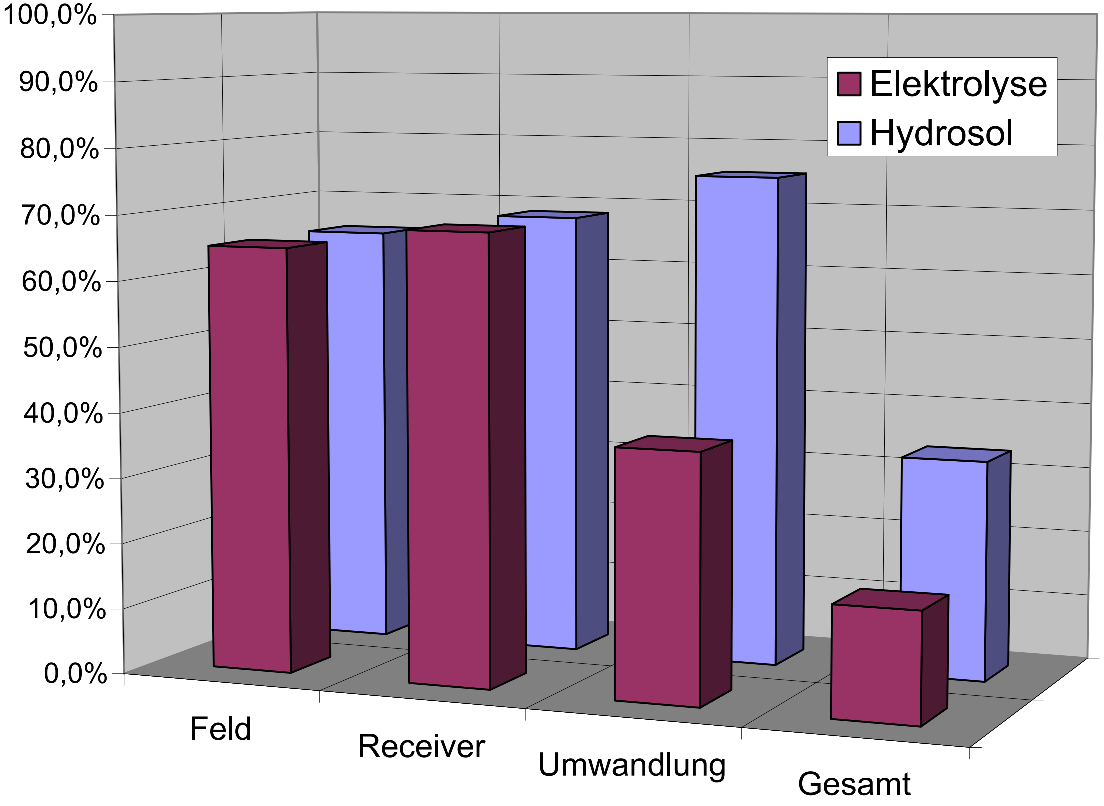
$\eta_{reactor} = 0.20 - 0.28$

$$\eta_{(reactor)} = (Q_{sensible} + \text{mass flow}_{(H2)} * HHV_{(H2)}) / Q_{solar}$$

$\eta_{process} = 0.05 - 0.09$

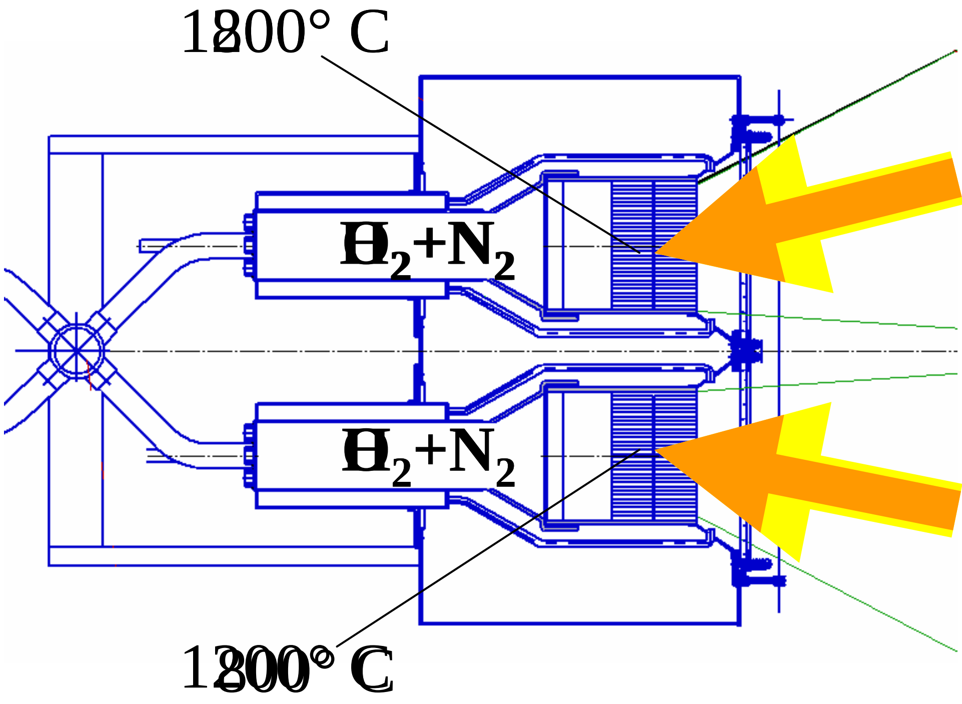
$$\eta_{process} = (\text{mass flow}_{(H2)} * HHV_{(H2)}) / Q_{solar}$$

Effizienzvergleich HYDROSOL – Elektrolyse



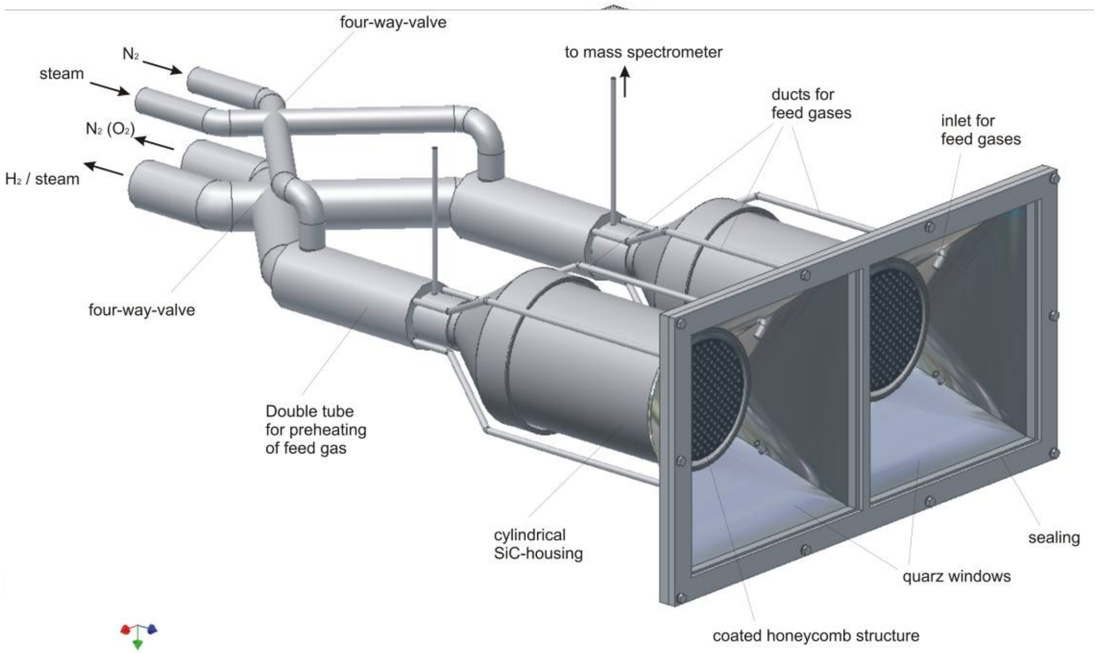
Reactor for continuous hydrogen production:

- Reactor with two modules
- Two different alternating processes:
  - Production: 800°C, water steam, nitrogen, exothermic
  - Regeneration: 1200°C, nitrogen, endothermic
- Transient steps like
  - Switching between half cycle
  - Start-up / Shutdown
- Temperature gradient on the coated structure
- Fluctuating irradiation (daily / annually)

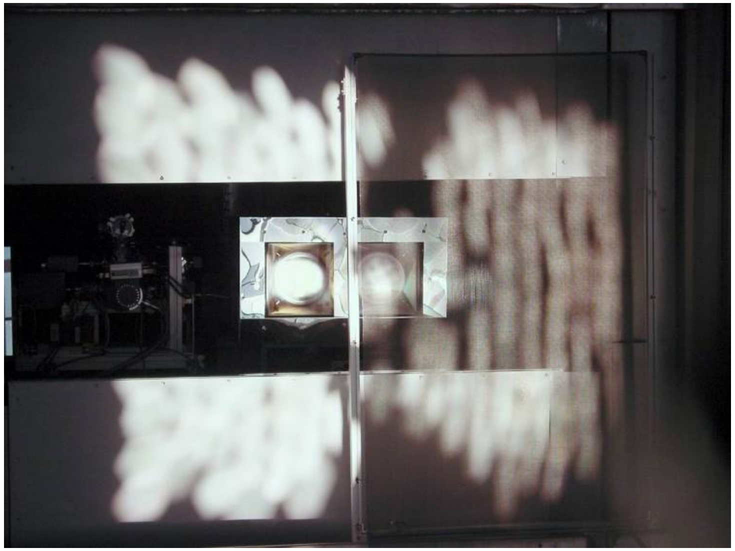


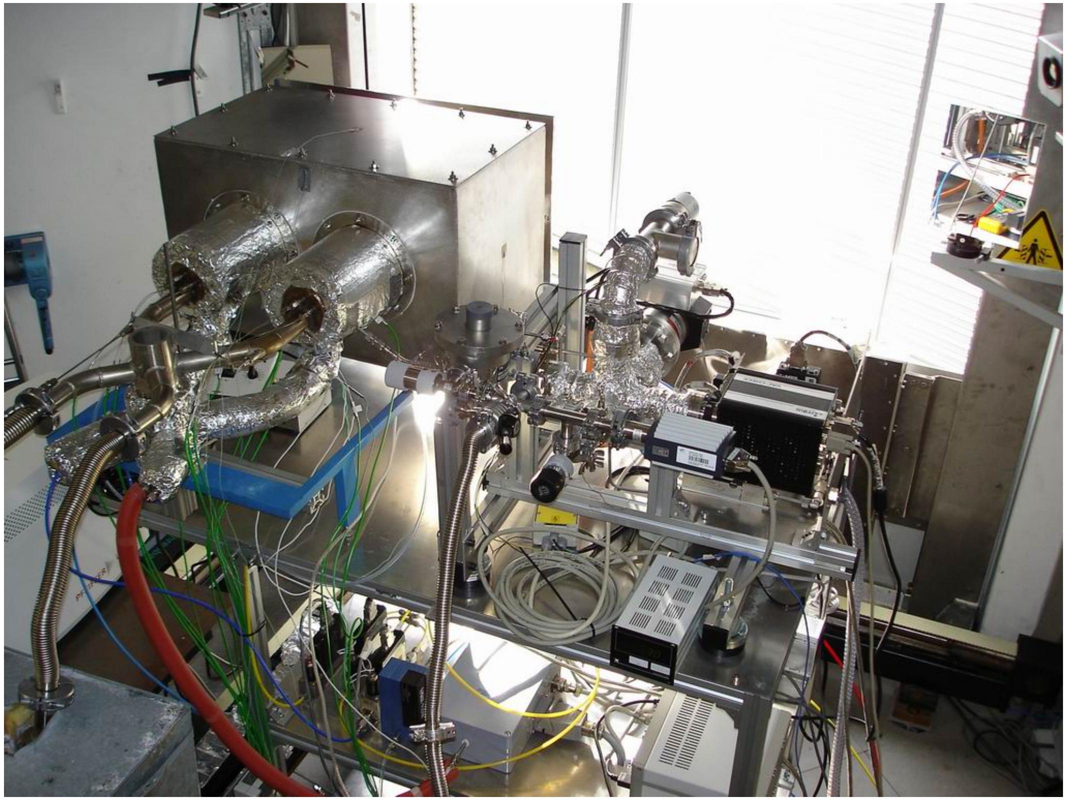
Reactor for continuous hydrogen production:

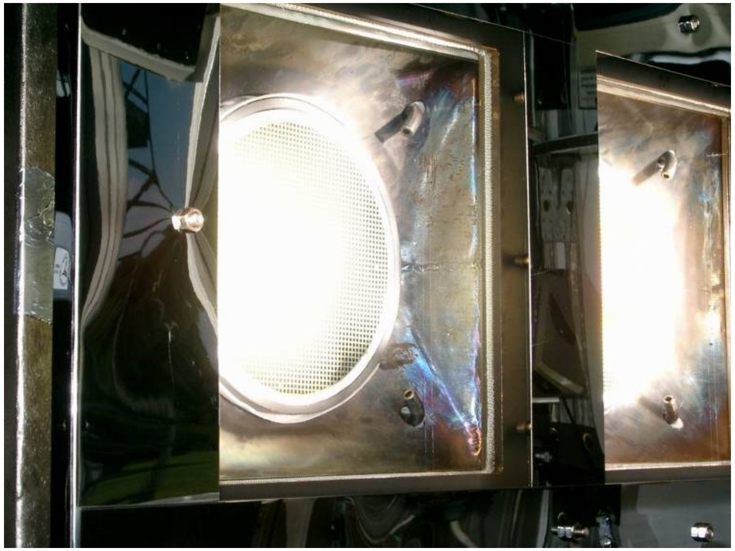
- 15 kW_{th} two chamber system
- Continuous hydrogen production
- Four way valve
- Preheating of feed gas
- Measure point for mass-spectrometry
- Quartz window



The „Conti-Reactor“ during test-operation



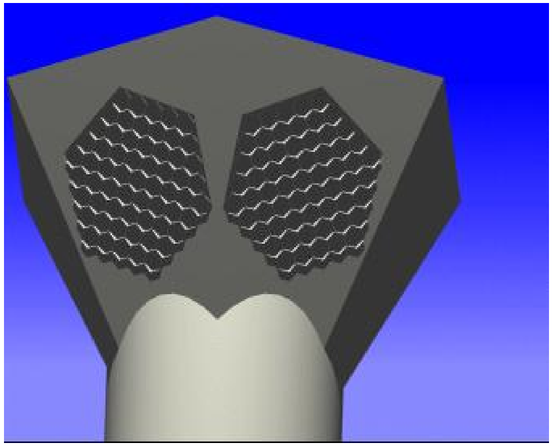


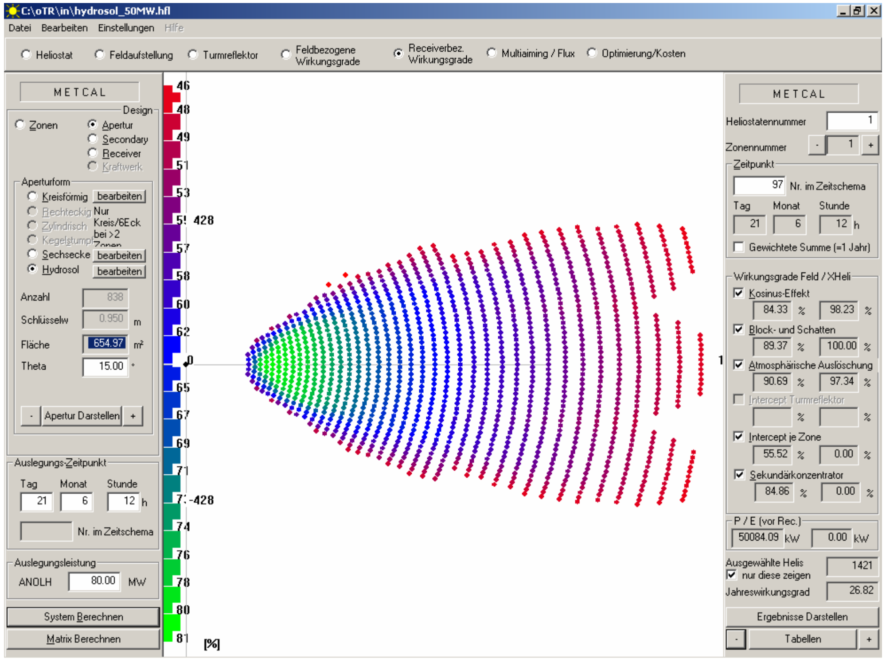


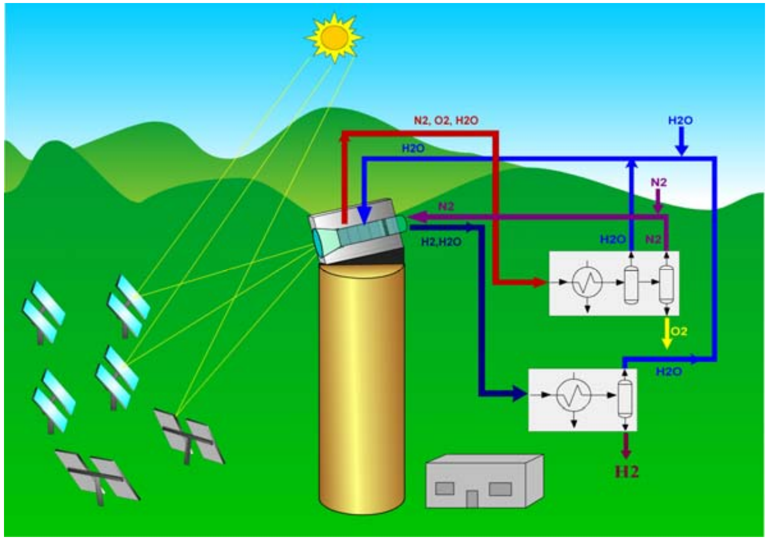
HYDROSOL II

- Start 2006
- New additional Partner CIEMAT
- 100 kW_{th}-scale
- Quasi continuous hydrogen production
- 2 modules: production/regeneration
- Use of 9 coated squared ceramic structures (150mm x 150mm x 50mm)
- Installation at SSPS Tower on PSA in the 2nd half of 2007

HYDROSOL – Design Study







Results of Simulation

- $P_{tot,d}$ = 200 MW at noon on June 21st
- 3264 heliostats needed, which is equivalent to $A_{mir,tot}$ = 396 000 m²
- Land area of 2.0 km²
- Tower height: 230 m
- Annual production: P_{H2} = 238 GWh(HHV H_2)/a or V_{H2} = 80 Mio. Nm³/a or 7200 t/a.

Investment costs

Component	Unit price	Units	Total [€]
Heliostats	130 €/m²	3264 x 121.34 m²	51 500 000
Land	1 M$/km²	2.0 km²	2 000 000
Tower		(230 m)	5 100 000
Buildings	3 M€	1	3 000 000
HT receiver modules	40 000 €	502	20 100 000
LT receiver modules	17 000 €	561	9 500 000
Heat exchanger	3 M€/50MW	200 MW	12 000 000
Heat recovery boiler	1 M€/ 50MW	200 MW	4 000 000
Pumps & Piping	.4 M€ / 50MW	200 MW	1 600 000
Sum			**149 600 000**
Safety surcharge	10%		15 000 000
Total Investment I_0			**165 000 000**

Operational costs

Fixed costs	Unit price	Units	Total [€/a]
Personal	70 000 €/a	10	700 000
Insurance	2% of I_0		3 300 000
Maintenance	4 % of I_0		6 600 000
Redox System	3.7 M€/a for 50 MW	(for 200 MW)	14 800 000
Variable costs			
Separation Unit	2633 k€/a for 50 MW	(for 200 MW)	10 532 000
Nitrogen	294 k€/a for 50 MW		1 176 000
Water	11 k€/a for 50 MW		44 000
Electricity	1777 k€/a for 50 MW		7 108 000
Sum			**44 260 000**

Conclusion and Outlook

- Solar fuels have a huge potential to become the energy carriers of the future especially for mobile applications
- Thermal production is more efficient than electrolysis
- The solar research of DLR will continue its work on reforming and cracking of carbonaceous materials (e.g. natural gas) because of the short and medium term chances of these technologies
- Solar thermal up-grading of biomass is not efficient
- Thermochemical cycles for hydrogen production are for long term use
- Three main problems have to be solved:
  - Heat provision
  - Material properties of components and reactants
  - Product separation
- The aim is to produce renewable fuels by ecologically and economically reasonable technologies

Acknowledgement

The Projects HYDROSOL, HYDROSOL- II; HYTHEC, SCR, SOLASYS, SOLREF, SOLHYCARB, Hi2H2, and INNOHYP-CA have been co-funded by the European Commission.

HYDROSOL has been awarded

- Eco Tech Award Expo 2005, Tokyo
- IPHE Technical Achievement Award 2006
- Descartes Prize 2006