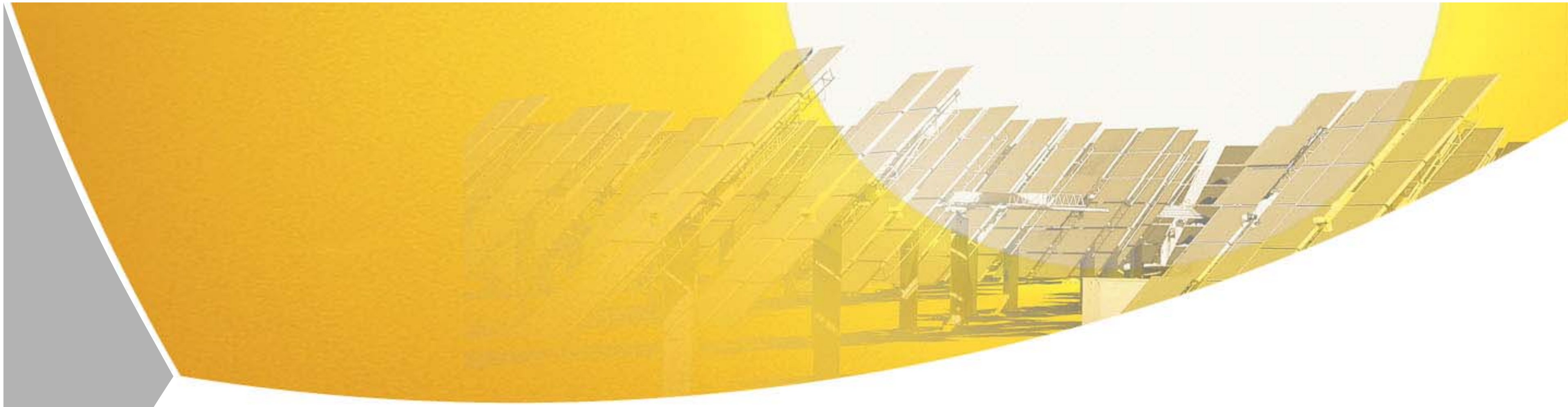

Solar Hydrogen

Stellenbosch University, September 2nd, 2010

Dr. Christian Sattler

DLR – German Aerospace Center - Solar Research

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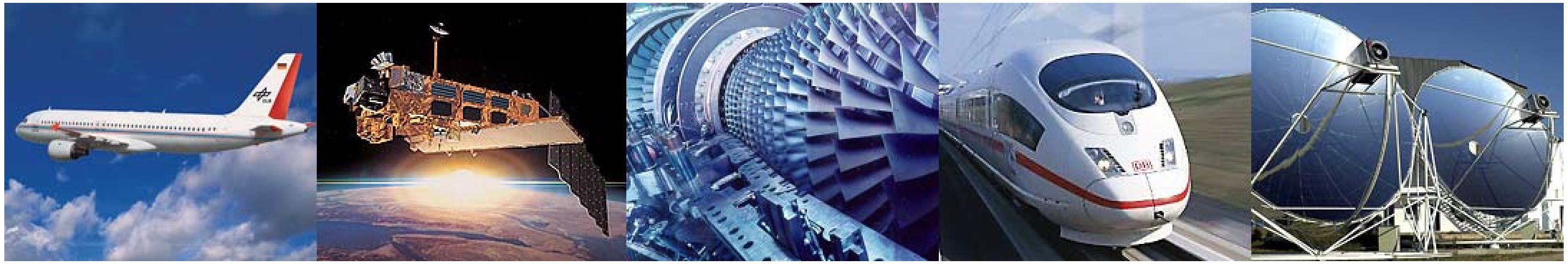
Overview

- Introduction of DLR
  - Energy
- Solar Hydrogen
  - From Fossil Recourses
  - Thermochemical Cycles
- HYDROSOL, HYDROSOL 2, HYDRSOOL 3-D
- Summary and Outlook

DLR
German Aerospace Center



- Research Institution
- Space Agency
- Project Management Agency

Research Areas

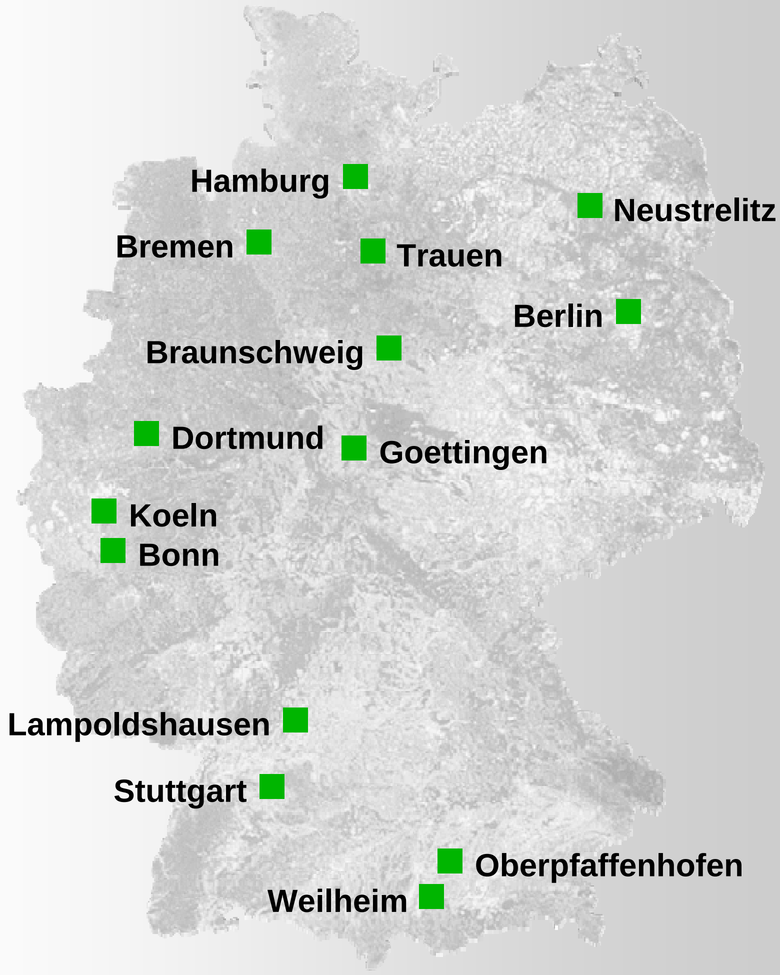
- Aeronautics
- Space
- Transport
- Energy
- Space Agency
- Project Management Agency

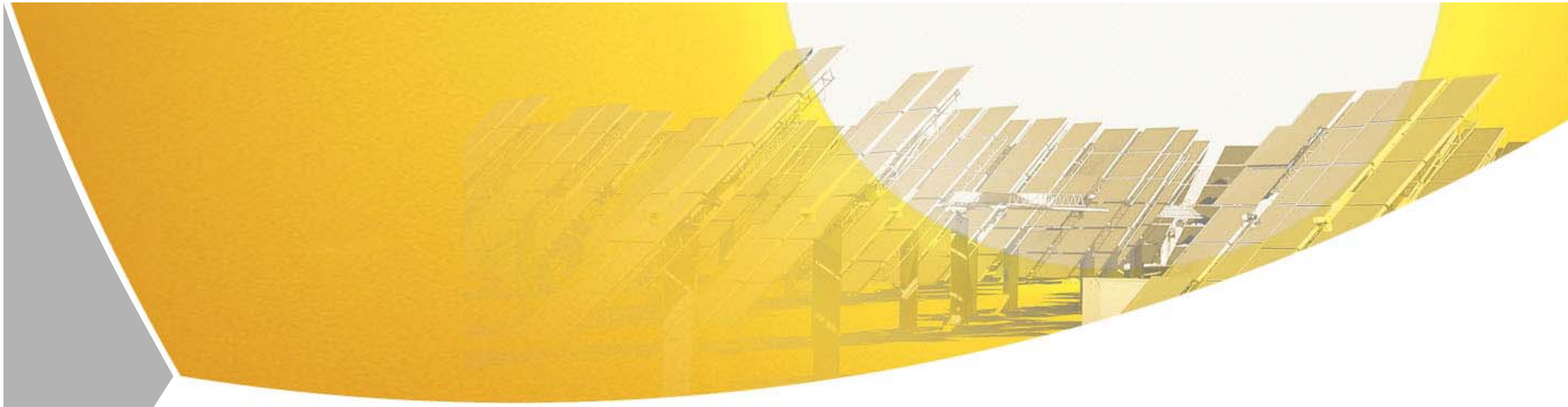
Locations and employees

6500 employees across
29 research institutes and
facilities at

- 13 sites.

Offices in Brussels,
Paris, Washington, and Almería
(plus permanent Delegation on the
Plataforma Solar de Almería)



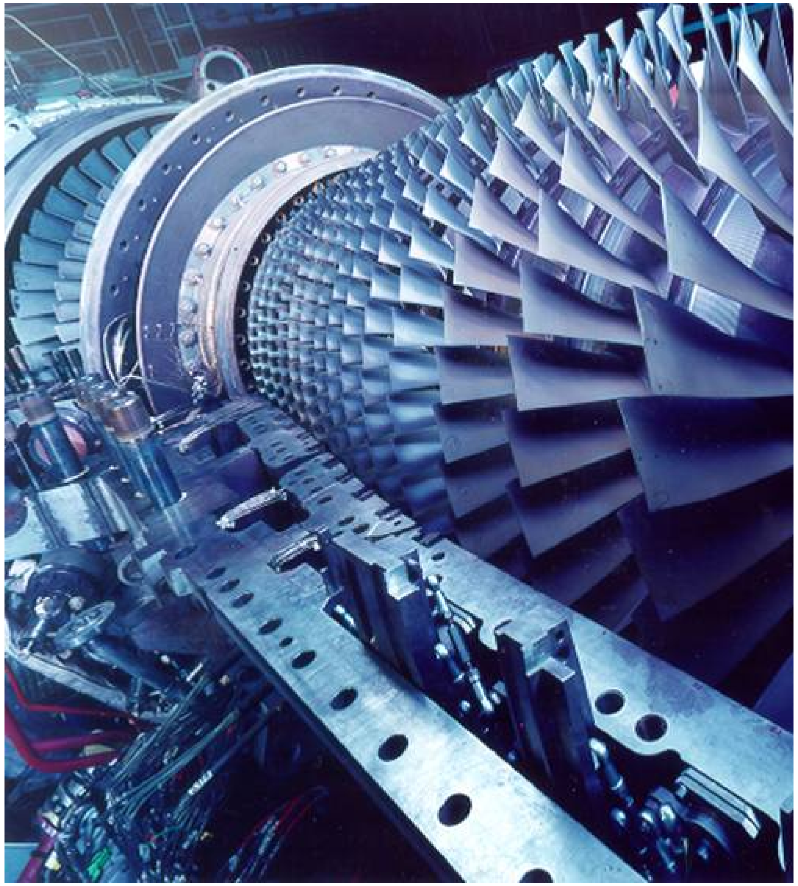


Energy

DLR Energy Research Area

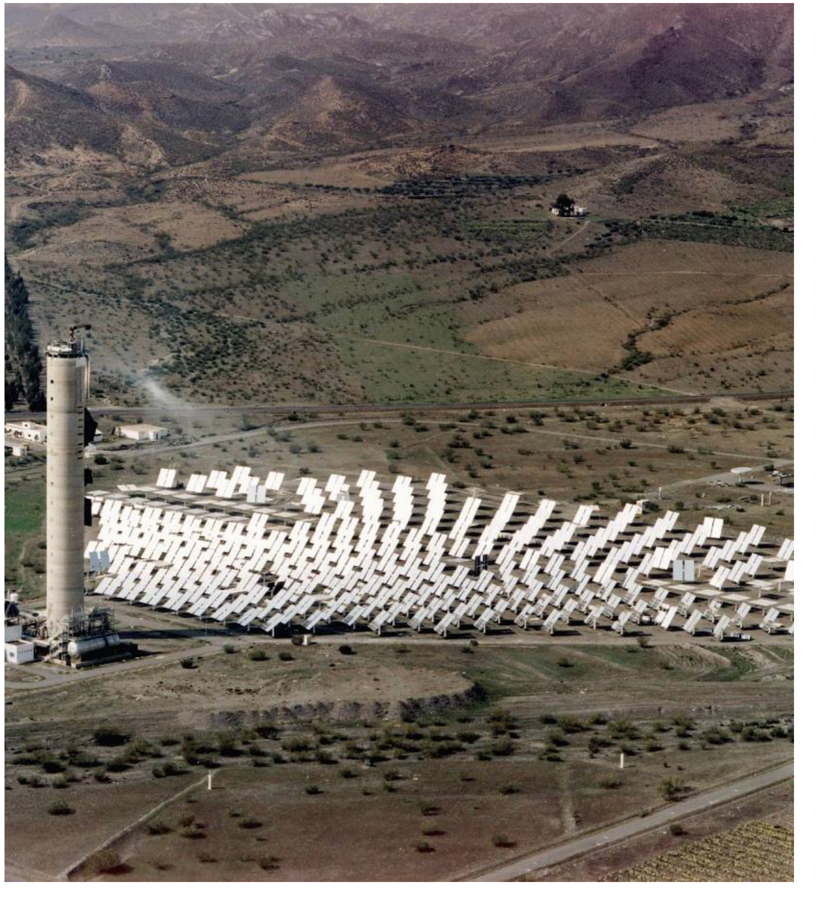
DLR Energy Research concentrates on:

- CO_2 avoidance through efficiency and renewable energies
- synergies within the DLR
- major research specific themes that are relevant to the energy economy
- Second largest research centre in Germany for non-nuclear energy
- Approx. 400 employees



Energy Research Program Themes

- Efficient and environmentally compatible fossil-fuel power stations
  (turbo machines, combustion chambers, heat exchangers)
- Solar thermal power plant technology, solar materials conversion
- Thermal and chemical energy storage
- High and low temperature fuel cells
- Systems analysis and technology assessment



Portfolio of Competences – Energy

Systems analysis and technology assessment

	Fuel cells	Power plant technology	Concentrating solar systems
Efficient energy conversion	Materials Manufacturing techniques Heat management	Combustion Turbo-machines Gas turbine systems Heat exchangers	
	Hybrid power plants	Solar gas turbines	
Renewable energies	Fuel cells with alternative fuels	Solar gas turbines Heat storage Gas turbines with alternative fuels	Solar hydrogen production Solar power plants Solar process heat

Simulation/modelling

Solar Hydrogen

Vision

- Producing hydrogen for mass markets means implementing as efficient processes as possible to convert available energy sources like renewables or nuclear into the chemical energy vector.
  (De Beni G. 1970; Marchetti 1973; Winter 2000)

- Hydrogen should be produced from water
  - to reduce dependencies on fossil fuels
  - To reduces environmental impact

Technical and Economic Efficiency

Technical: In which process is the most energy stored in the hydrogen

Is the process technical feasible?

Are there any knock-out criteria?

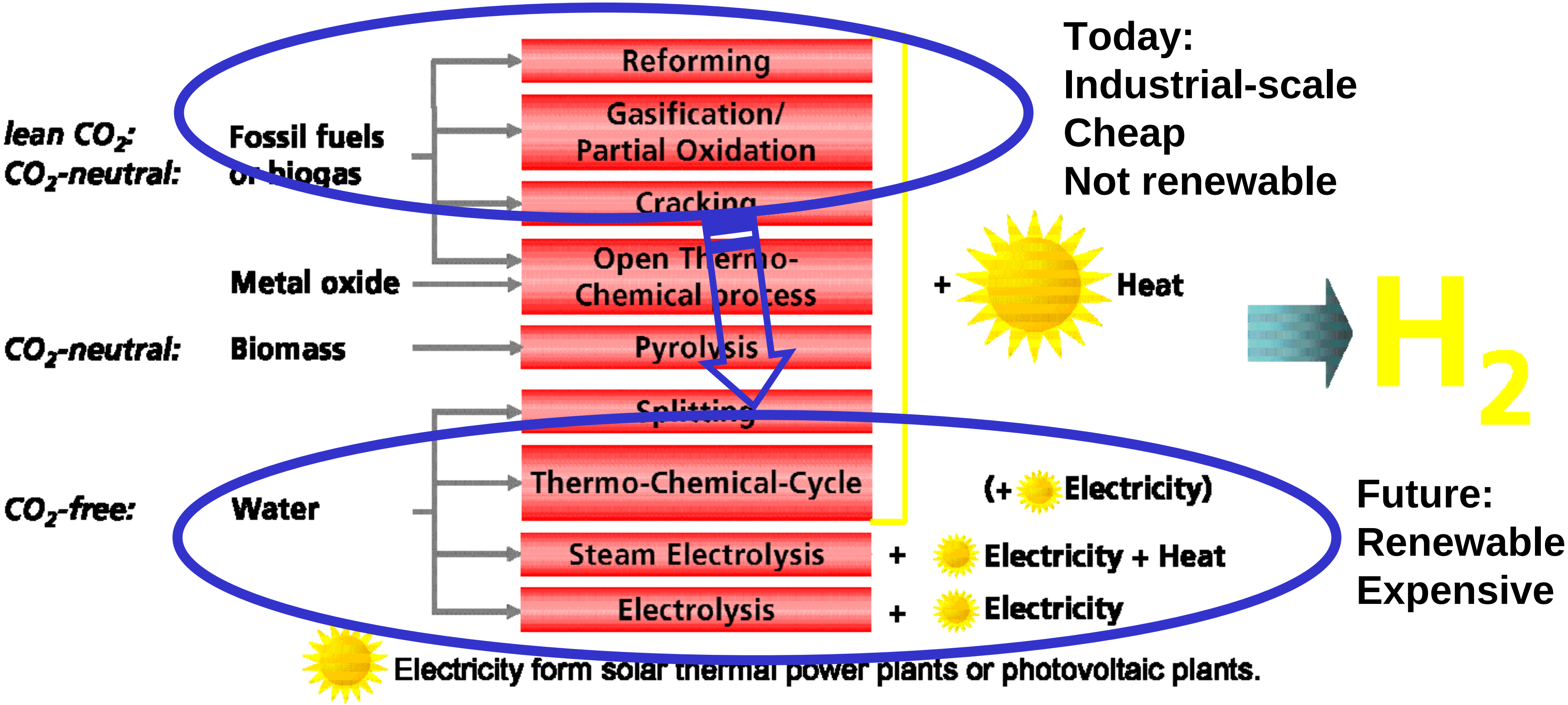
Economic: Is the product (hydrogen) cost competitive?

Are there any other economic reasons that make the process not competitive?

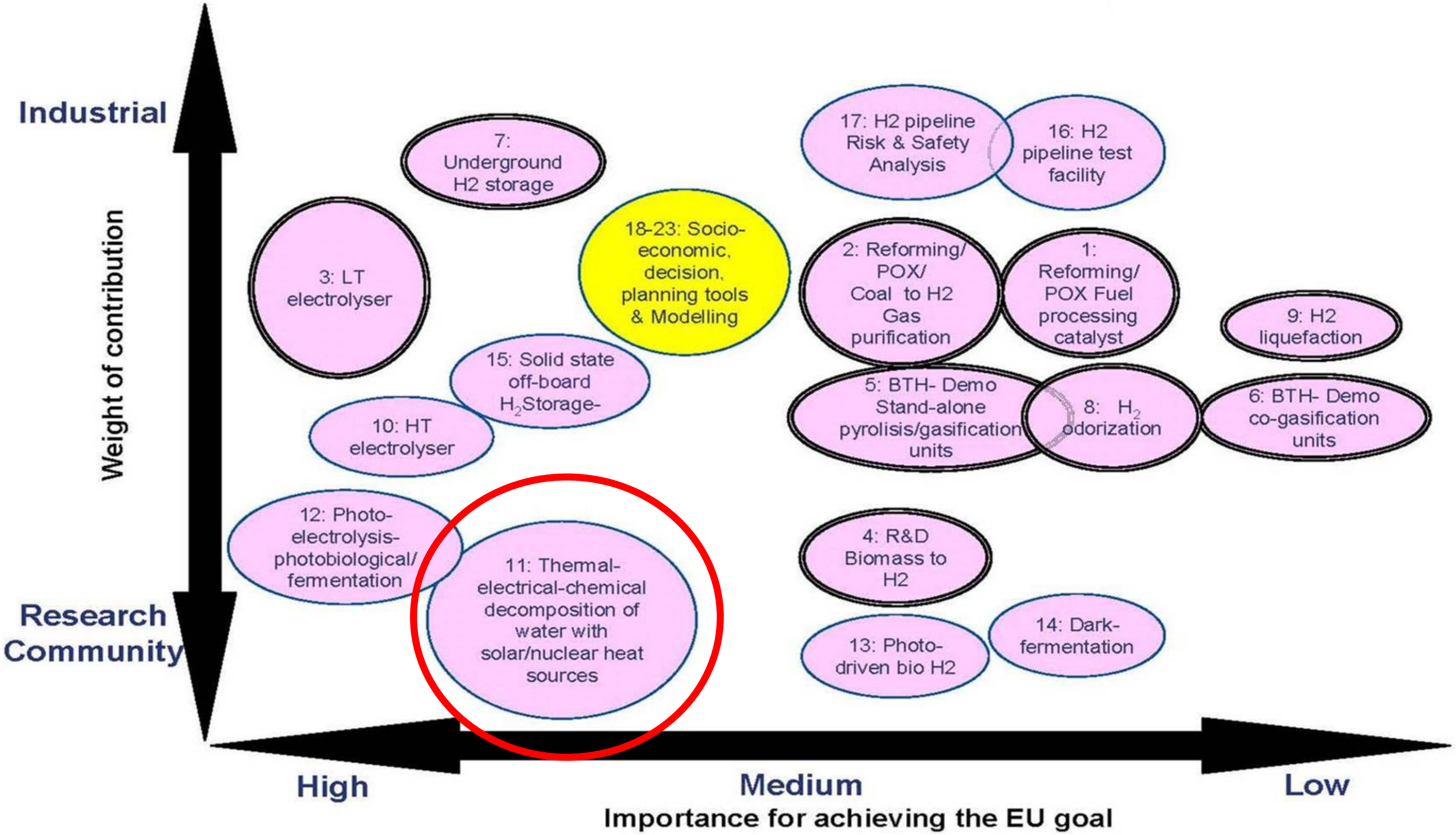
Hydrogen Production Today

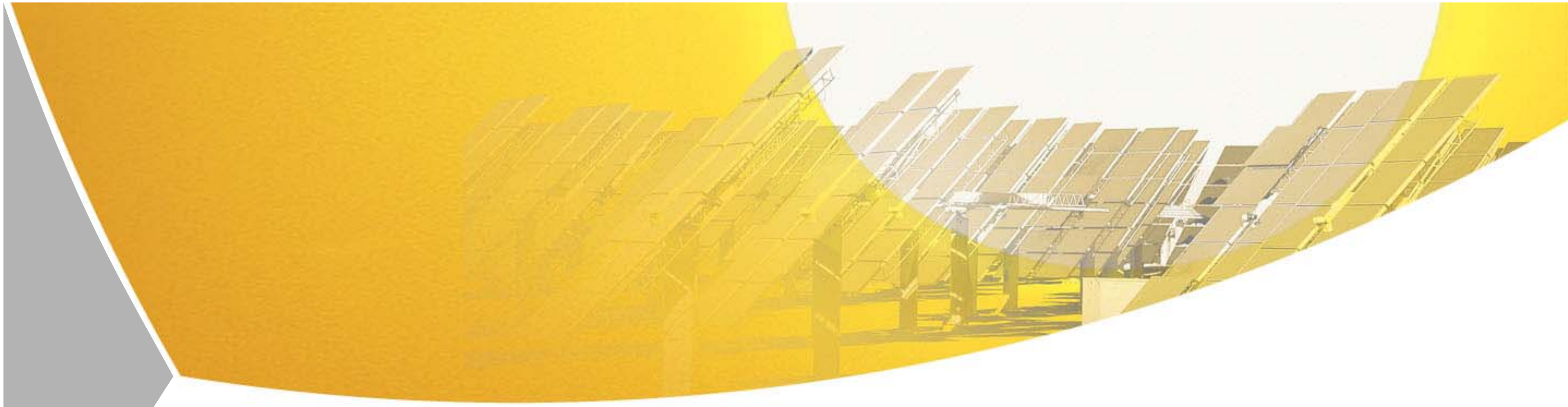
- Steam Methane Reforming
  - Thermal efficiency 78%
  - 1 kg H_2 by means of SMR yields to 9.42 kg of CO_2
  - The production cost of hydrogen is estimated at 0.04 €/kWh (1.33 €/kg)
- Coal Gasification
  - The Lurgi Process (Fixed-Bed) 500 – 1000 °C
  - The Winkler Process (Fluidized-Bed) 800 - 1100 °C
  - The Koppers-Totzek/Texaco Process (Entrained-Bed) 1040 – 1540 °C
    - Thermal efficiency 58 - 63%
    - 23 kg CO_2 / kg H_2
  - Hydrogen costs from coal gasification are 1.21 to 1.79 €/kg H_2(coal price not reported)
- Partial Oxidation
  - 1300 - 1500 °C
  - 1.45 – 1.67 €/kg

Solar Thermal Processes for Hydrogen Production



Production-, Storage- and Infrastructure topics of the European Hydrogen and Fuel Cell JTI



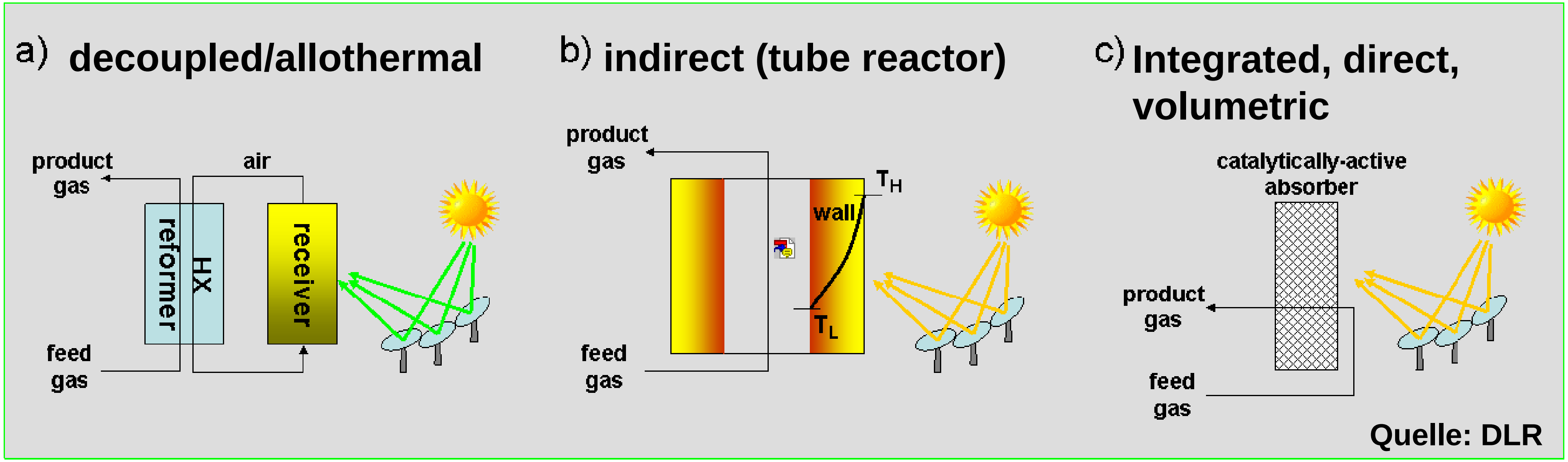


Solar Hydrogen from Hybrid Fossil Processes

Carbon Based Transition Processes

- Starting from applied technologies
- Reduced risk compared to water splitting technologies
- Solar Reforming of Natural Gas
  - Development by a number of groups since at least 25 years
  - Cost are estimated to 1.4 €/kg H_2
- Solar Gasification and Reforming of Petcoke
  - Development by ETH Zurich, CIEMAT, and PDVSA
  - Cost are estimated to about 2.1 €/kg H_2
- SOLZINC – Carbothermal reduction of ZnO
  - Pilot reactor successfully tested
  - Zinc is produced not hydrogen!
- Solar Cracking of Methane
  - No CO_2 emission but C, C might be a product too
  - challenging reactor design: solids and high temperatures

Solar Steam Methane Reforming – Technologies



- Reformer heated externally (700 to 850°C)
- Optional heat storage (up to 24/7)
- E.g. DLR Project ASTERIX

- Irradiated reformer tubes (up to 850°C), temperature gradient
- Approx. 70 % Reformer-η
- Development: CSIRO, Australia and in Japan; Research in Germany and Israel
- Australian solar gas plant in preparation

- Catalytic active direct irradiated absorber
- Approx. 90 % Reformer-η
- High solar flux, works only by direct solar radiation
- DLR coordinated projects: SCR, Solasys, Solref; Research in Israel, Japan

Direct heated volumetric receiver: SOLASYS, SOLREF (EU FP4, FP6)

- Pressurised solar receiver,
  - Developed by DLR
  - Tested at the Weizmann Institute of Science, Israel
- Power coupled into the process gas: 220 kW_{th} and 400 kW_{th}
- Reforming temperature: between 765°C and 1000°C
- Pressure: SOLASYS 9 bar, SOLREF 15 bar
- Methane Conversion: max. 78 % (= theor. balance)
- DLR (D), WIS (IL), ETH (CH), Johnson Matthey (UK), APTL (GR), HYGEAR (NL), SHAP (I)

Assessment of relevant H_2 pathways until 2020

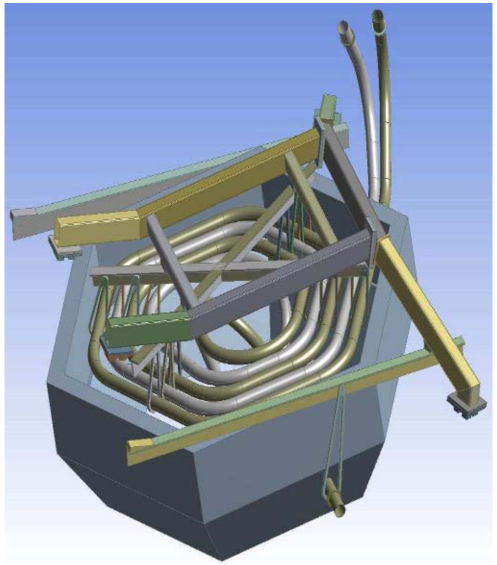
including NG Solar-SMR for comparison issues

	NG SMR	NG Solar-SMR	Grid Electricity electrolysis	Wind electrolysis	Biomass
H_2 production cost	8* €/GJ	12* €/GJ	31 €/GJ	50-67 €/GJ	25-33 €/GJ
Positive impact on security of energy supply	modest	modest - high	high	high	high
Positive impact on GHG emission reduction	neutral - modest	modest - high	negative -neutral	high	high

***assuming a NG price of 4€/GJ; NG Solar-SMR: expected costs for large scale, solar-only**

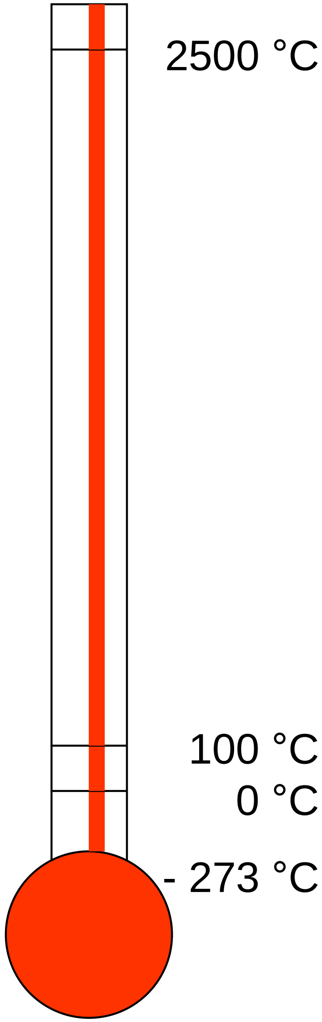
Project Perspectives

- The consortium forces the realisation of the a prototype reforming plant
- Link with Australian CSIRO by an ongoing IPHE project
- Funding was assured in October 2009
- Development phase of the joint project
- SOLREF receiver will run on a second tower at the CSIRO Solar Centre in Newcastle, NSW

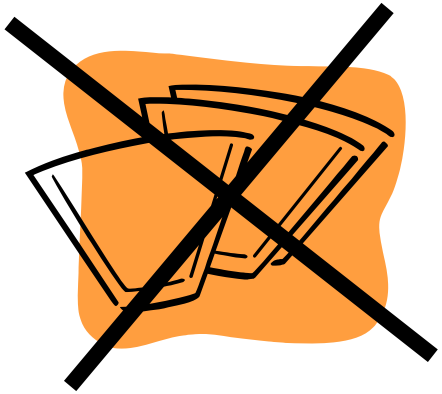


Thermochemical Cycles

Thermochemical Water Splitting



PROBLEMS!



- Hydrogen + Oxygen = explosive gas!
  - Dangerous
  - Separation?

- 2500 °C Materials
  - Special ceramics – difficult to handle, expensive

- 2500 °C Temperature
  - How could such high temperatures be achieved?
  - Efficiency?

Sollution

O_2

50 °C

1250 °C

H_2O

Are the problems solved now?

- Still high temperatures
- Materials
- Chemical reactions
- Efficiency

Thermochemical Cycle

- Firstly developed in the oil crises of the 1970s
- Use of nuclear energy to produce an energy carrier
- Mainly in the USA (General Atamics, Westinghouse), but also in Europe (FZJ, JRC Ispra) and Japan (JAEA)
- Up to 900 different cycles are known
- Main groups:
  - Sulphur cycles
  - Volatile metal oxide cycles
  - Non-volatile metal oxie cycles
  - Low temperature cycles
- In the 1980s and 1990s the interst went down because of lower oil prices
- Come back in the 2000s
  - Solar thermal more in the focus
  - Studies to identify the most promising cycles (e.g. USA, France)

Thermochemical vs. Electrochemical?

- Thermochemical
  - No conversion steps necessary = possibly very high efficiency

- Electrochemical
  - Conversion steps necessary for power production = lower efficiency

- No contradiction: use energy forms as efficient as possible

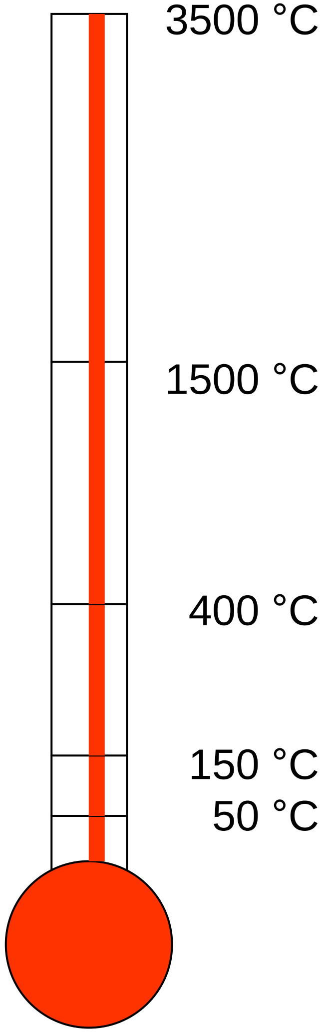
Promising and well researched Cycles

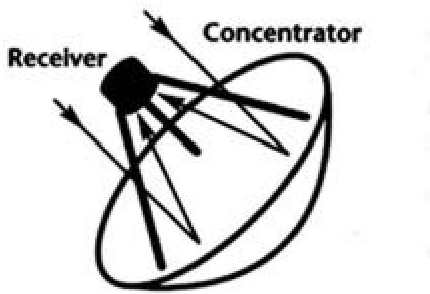
	Steps	Maximum Temperature (°C)	LHV Efficiency (%)
Sulphur Cycles			
Hybrid Sulphur (Westinghouse, ISPRA Mark 11)	2	900 (1150 without catalyst)	43
Sulphur Iodine (General Atomics, ISPRA Mark 16)	3	900 (1150 without catalyst)	38
Volatile Metal Oxide Cycles			
Zinc/Zinc Oxide	2	1800	45
Hybrid Cadmium		1600	42
Non-volatile Metal Oxide Cycles			
Iron Oxide	2	2200	42
Cerium Oxide	2	2000	68
Ferrites	2	1100 – 1800	43
Low-Temperature Cycles			
Hybrid Copper Chlorine	4	530	39

Temperature nuclear

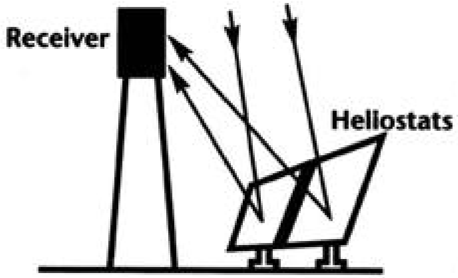
Reactor Type	Temperature (°C)	Carnot-Efficiency
Boiling Water Reactor	285	47%
RBMK (Graphite moderated)	285	47%
CANDU Reactor (Heavy Water Reactor)	300	48%
Pressurised Water Reactor	320	50%
Breeder Reactor, Sodium cooled	550	64%
Advanced Gas Cooled Reactor	650	68%
(Very) High Temperature Reactor	750+	71+%

Temperature – Concentrating Solar Power

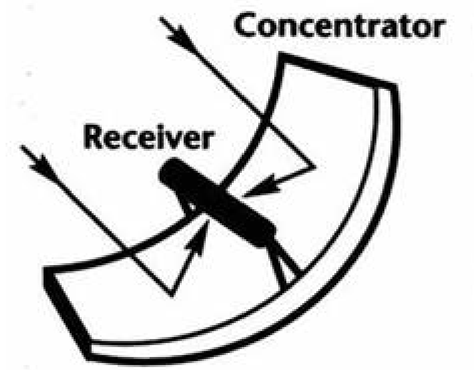




Paraboloid: Dish

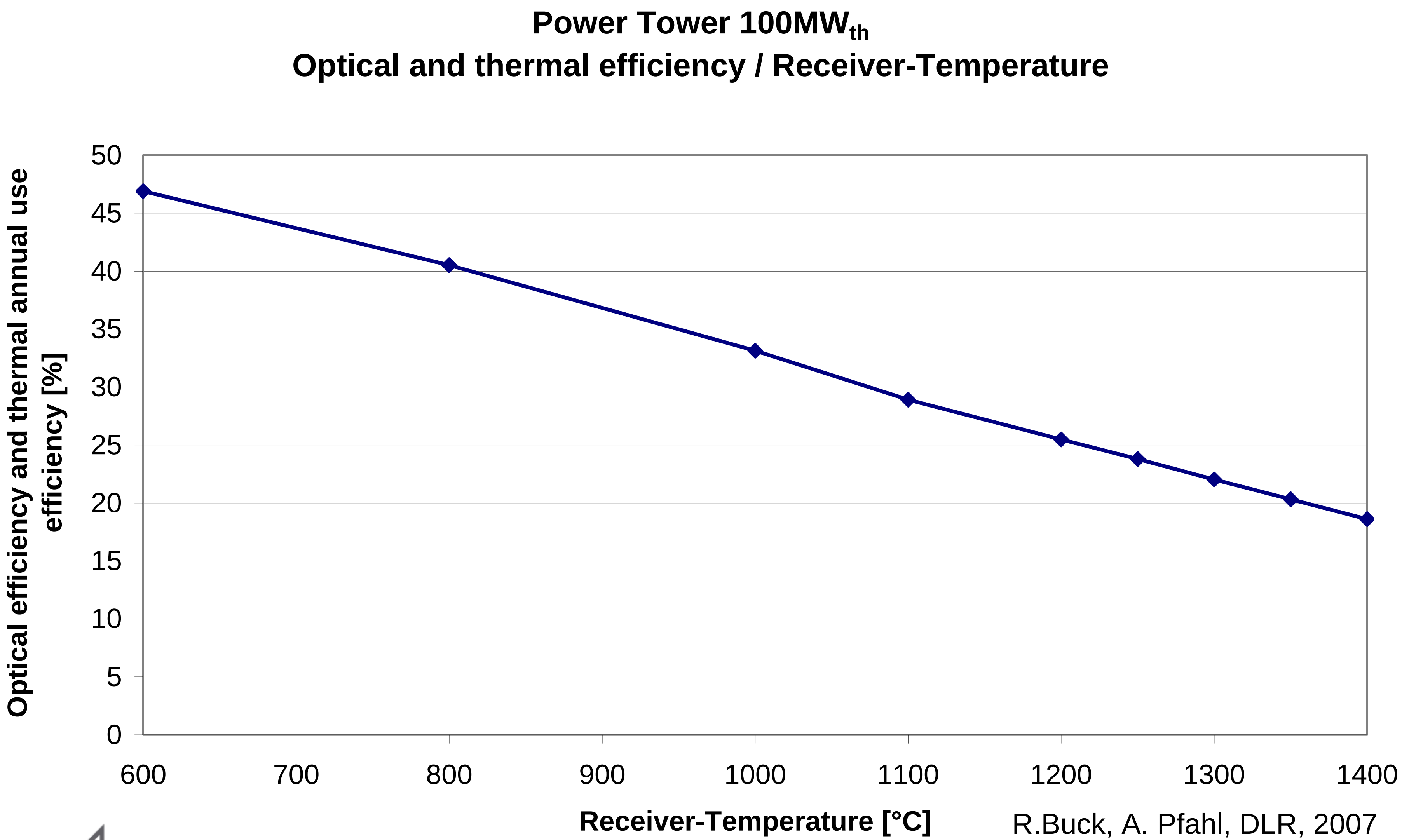


Solar tower
(Central Receiver System)



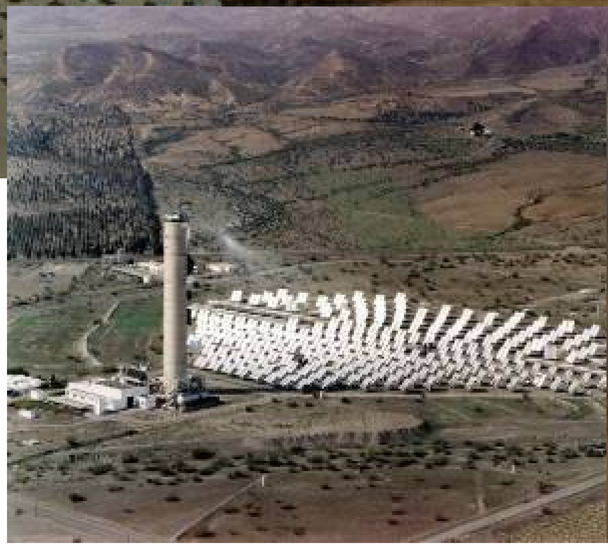
Parabolic trough

Annual Efficiency of Solar Power Towers



R.Buck, A. Pfahl, DLR, 2007

Solar Towers, “Central Receiver Systems”



- Solar-Two
- PSA
- PS10+20

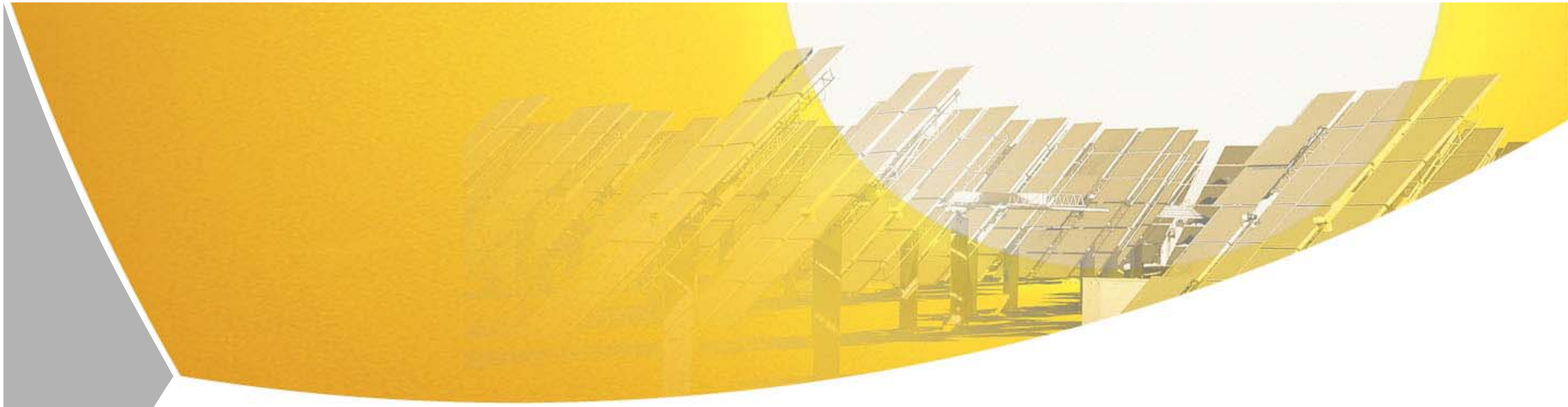
Efficiency comparison solar H_2 production from water, SANDIA 2008

Process	T [°C]	Solar plant	Solar-receiver + power [MWth]	η T/C (HHV)	η Optical	η Receiver	η Annual Efficiency Solar – H_2
Elctrolysis (+solar-thermal power)	NA	Actual Solar tower	Molten Salt 700	30%	57%	83%	14%
High temperature steam electrolysis	850	Future Solar tower	Particle 700	45%	57%	76,2%	20%
Hybrid Sulphur-process	850	Future Solar tower	Particle 700	51%	57%	76%	22%
Hybrid Copper Chlorine-process	600	Future Solar tower	Molten Salt 700	49%	57%	83%	23%
Nickel Manganese Ferrit Process	1800	Future Solar dish	Rotating Disc < 1	52%	77%	62%	25%

G.J. Kolb, R.B. Diver SAND 2008-1900

Water based processes

- Long term necessary for the de-carbonised H_2 society
- Benchmark: Renewable electricity + electrolysis
- Challenging technologies
- Metal/Metal oxide thermo-chemical Cycles
  - Zn/ZnO (3,58 – 4,12 €/kg)
  - Mixed Iron Oxides (Ferrites)
  - Already shown in the HYDROSOL project
  - Cost based on the small scale experiments are 7 €/kg
  - Calculated improvements will lead to 3,5 €/kg
- Sulphur Cycle Family
  - Developed for use with nuclear heat
  - Hybrid Sulfur (ISPRA Mark 11)
  - Cost calculation 0,8 €/kg H_2 nuclear
  - Sulphur-Iodine Process (ISPRA Mark 16)
  - Cost calculation 1,17 – 1,66 €/kg nuclear, 4,53 €/kg solar



HYDROSOL, HYDROSOL 2, HYDROSOL 3D

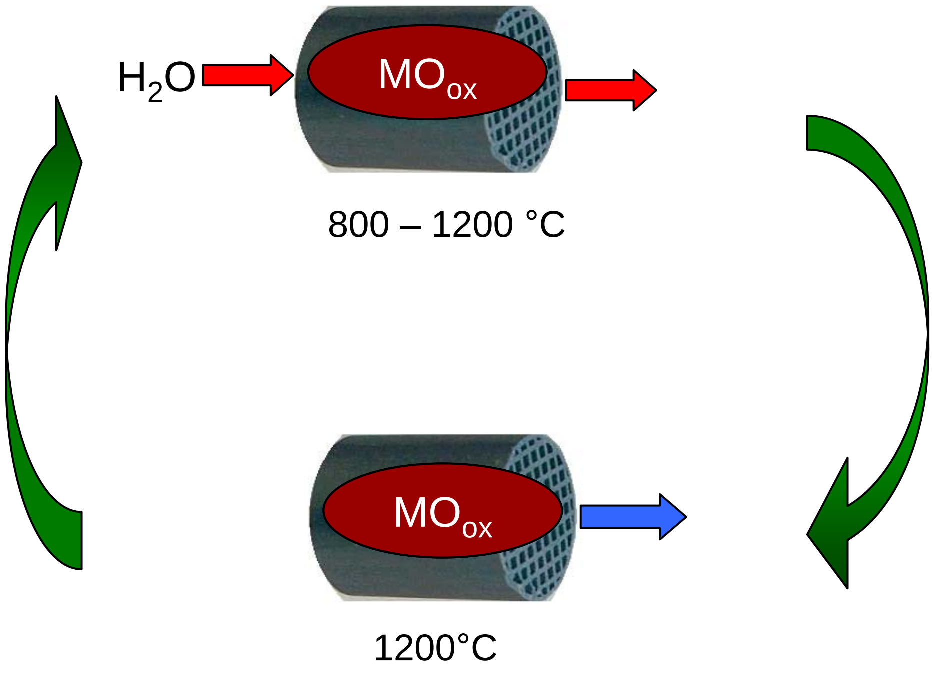
Thermochemical Cycle using Mixed Iron Oxides Process Operation

1. Step: Water Splitting

$H_2O + MO_{red} \rightarrow MO_{ox} + H_2$

2. Step: Regeneration

$MO_{ox} \rightarrow MO_{red} + ½ O_2$

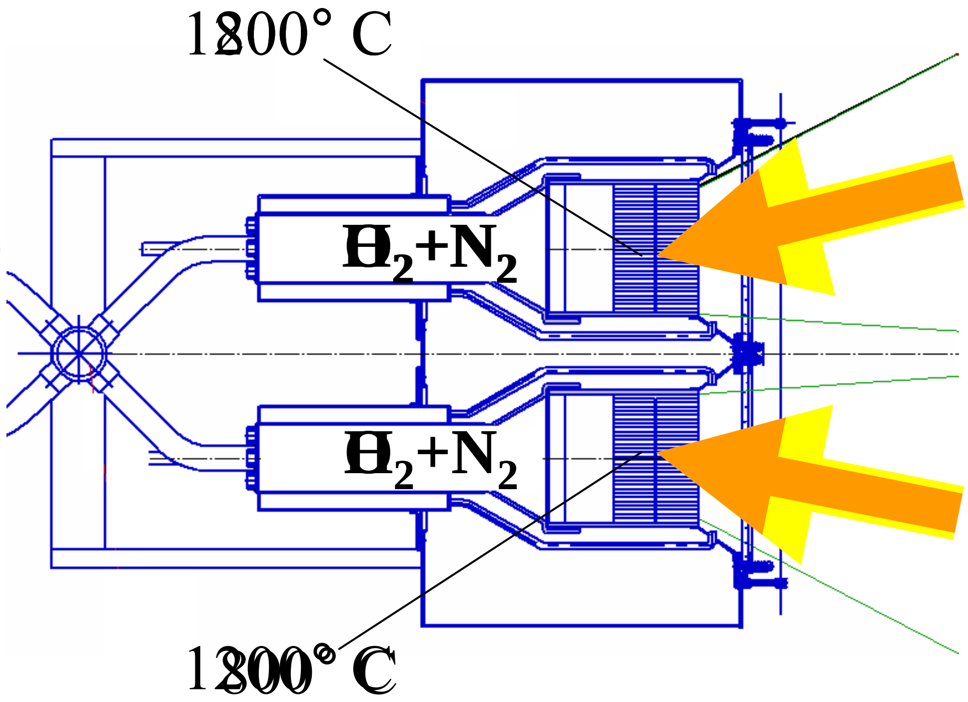


Net reaction: $H_2O \rightarrow H_2 + ½ O_2$

Redox materials used in the HYDROSOL-2 project:
ZnFeO, NiZnFeO

Reactor for continuous hydrogen production:

- Reactor with two modules
- 15 kW two-chamber system
- 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
- Closed system: quartz window
- Four-way-valve

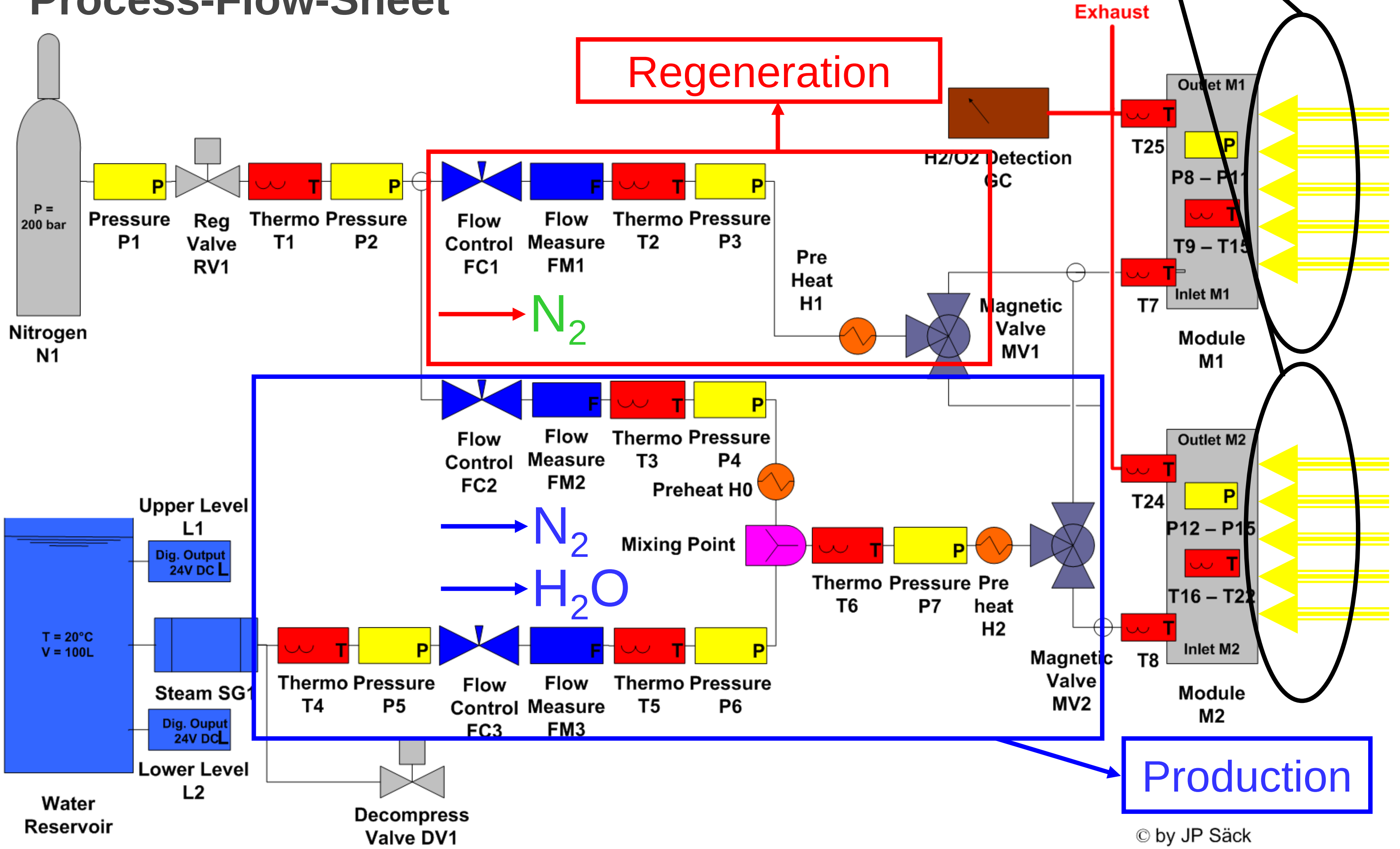


HYDROSOL II Pilot Reactor in Operation

Experiments – Process Control Software:

Set parameter
Solar Power

Process-Flow-Sheet

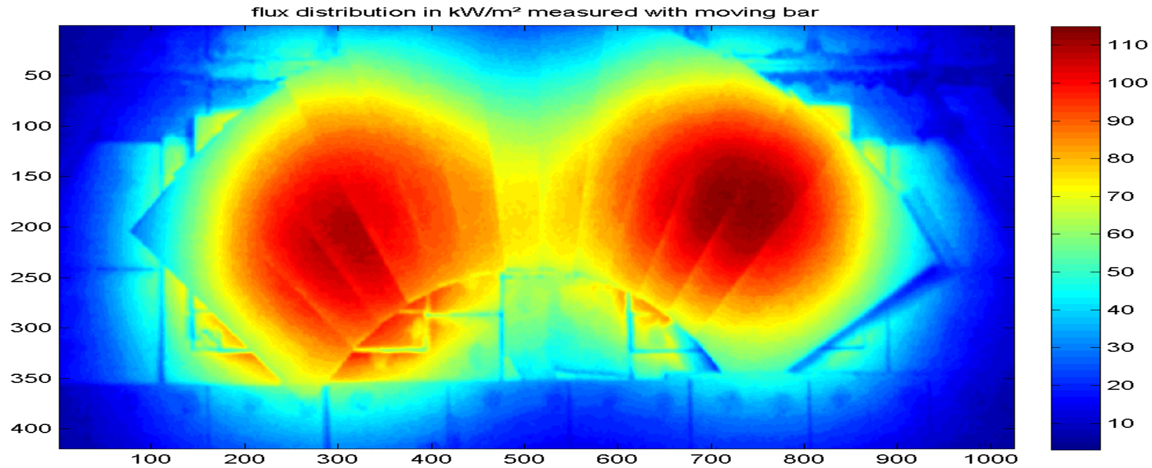


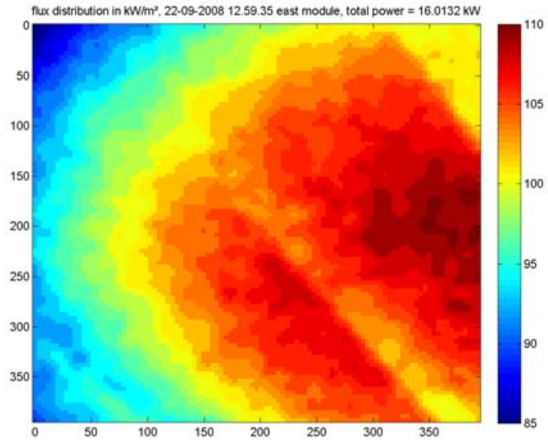
© by JP Säck

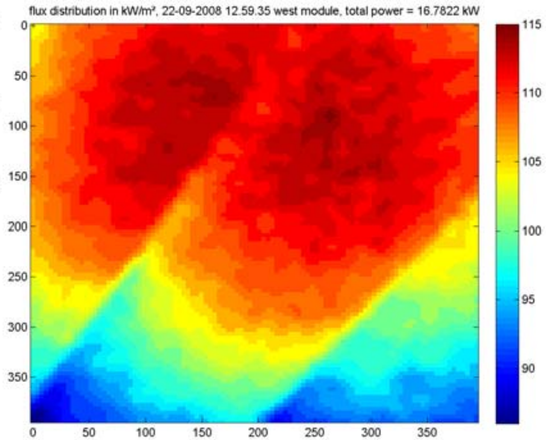
Experiments – Process Control Software:

Flux Measurement at test operation

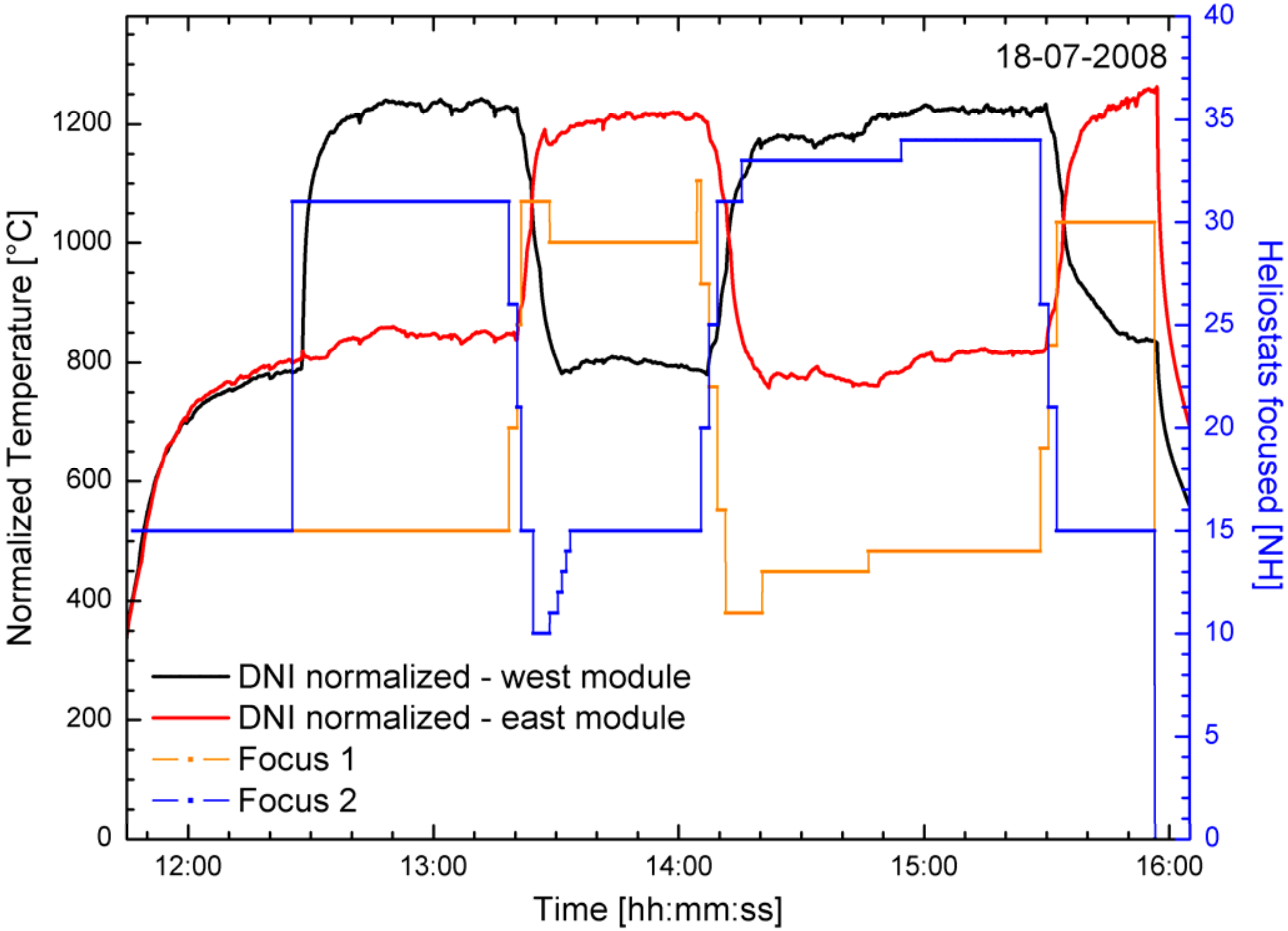
$Flux_{Max_{both\ Modules}} = 115 kW/m^2$



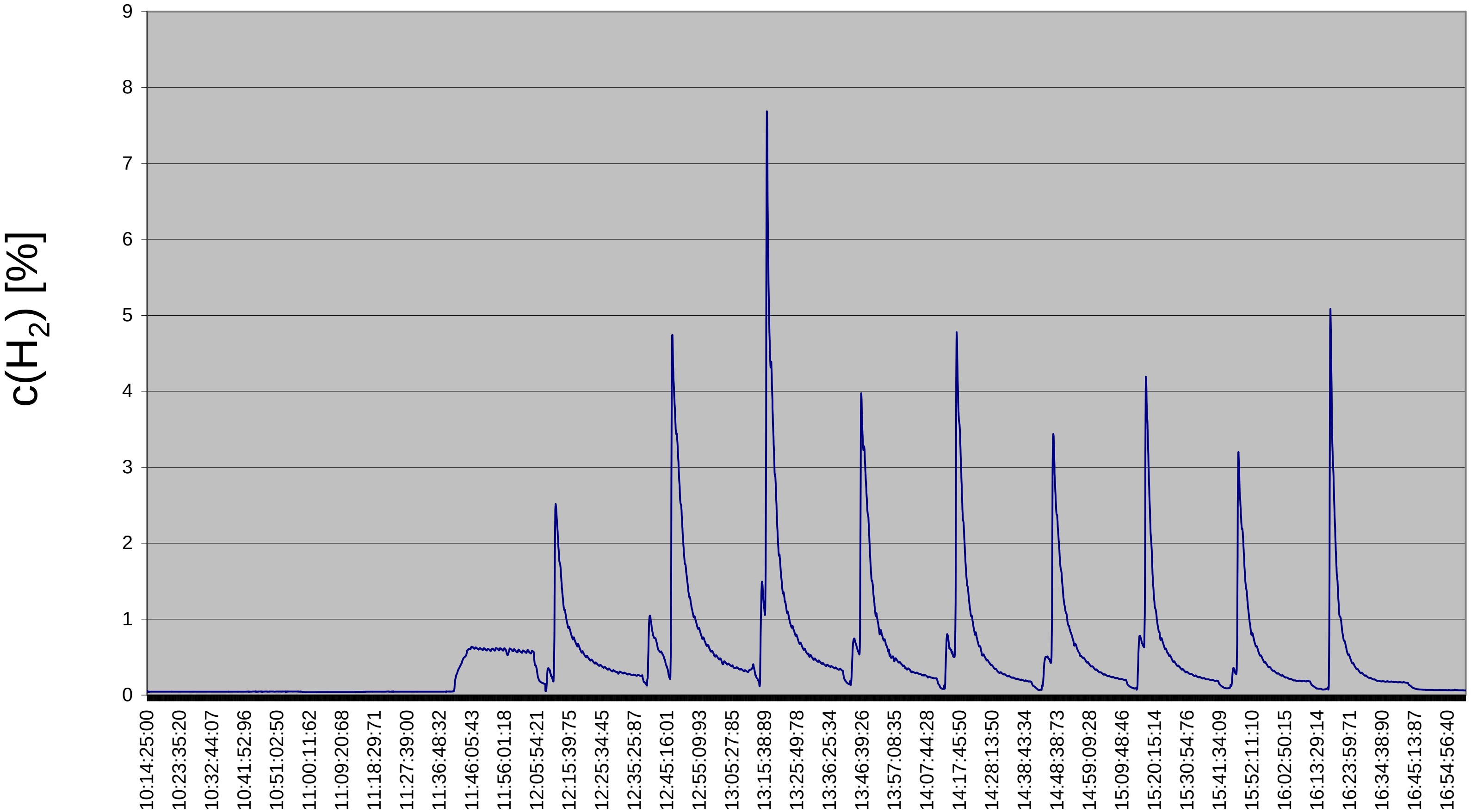




Results: Thermal cycling



Hydrogen production of 4th day of experimental series



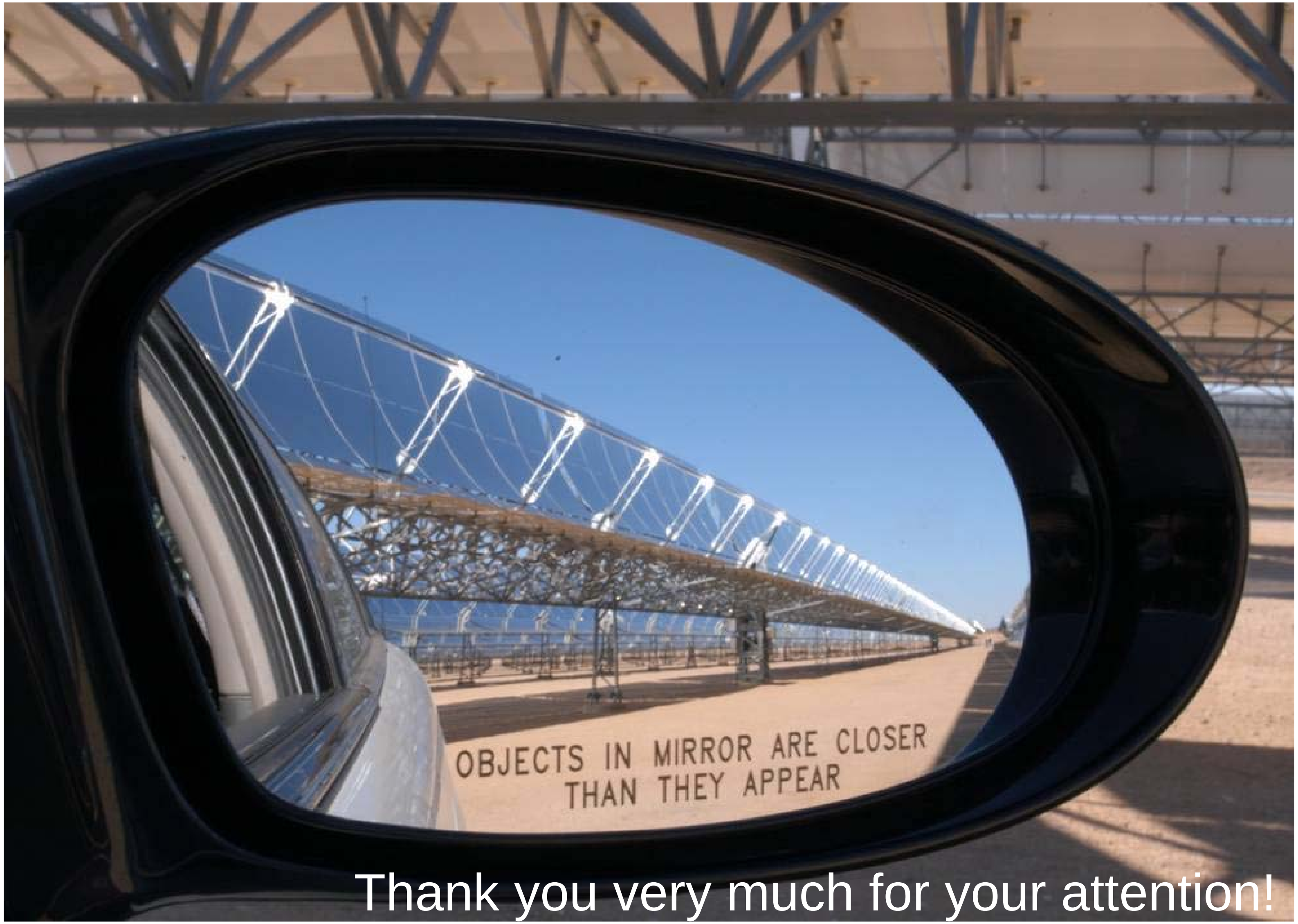
Summary and Outlook

- Technologies like solar steam reforming should be short term technologies to introduce solar technology into the chemical industry
- Thermochemical cycles will provide renewable hydrogen with very high efficiency compared to other renewable technologies
- The HYDROSOL reactor concept was scaled up in HYDROSOL 2 from the solar furnace to a 100 kW pilot plant on the tower of the PSA
- Topic of the ongoing HYDROSOL 3-D project is the design of a MW test plant
- Also sulfur cycles should be scaled-up since the development is already on a very advanced level and the temperature level is lower than of other TCCs

Acknowledgement

- The Projects
  HYDROSOL, HYDROSOL II; HYTHEC, HYCYCLES, Hi2H2, INNOHYP-CA, SOLHYCARB und SOLREF are co-funded by the European Commission
- HYDROSOL 3-D is co-funded by the European Joint Technology Initative on Hydrogen and Fuel Cells

- HYDROSOL was awarded
  - Eco Tech Award Expo 2005, Tokyo
  - IPHE Technical Achievement Award 2006
  - Descartes Research Price 2006



Thank you very much for your attention!