Solar Thermal Hydrogen Production
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Solar Research of DLR appr. 65 scientists, engineers, and technicians working at three sites: energetic utilization of concentrated solar radiation:

Köln-Porz  
(site and solar furnace)

Stuttgart  

Plataforma Solar de Almería, PSA, Spanien  
(permanent delegation)
Condition for industrial solar hydrogen production

Availability of appropriate solar receivers and processes
CSP - Concentrating Solar Power

- Parabolic Trough & Linear Fresnel Collectors
- Solar Tower
- Central Receiver
- Parabolic Dish
Solar Towers, Central Receiver Systems

- Solar-Two
- CESA-1
- PS10
Solar Furnace

Solar Radiant Power at Target up to ca. 25 kW
Irradiance > 5 MW/m²
High Power Lamp Arrangement

- Electrical Power Demand: 60 kW
- Maximum Radiant Power at Target (Objective): 25 kW
- Irradiance (Proof): > 4 MW/m²
Solar Hydrogen Generation
Solar Fuels

Solar fuels: chemically stored solar energy, potentially available for mobile applications

- Natural: → Biomass
- Synthetically: → Hydrogen, Syngas, other synthetic fuels
Hydrogen Today

- Hydrogen today mainly chemical intermediate, only marginal energetic applications
- Production
  600 – 700 Mrd. Nm³/a
  = 53 – 62 Mt/a
- Virtual Value
  100 Mrd. €/a
- Production growth rate appr. 10 %/a
- Only appr. 4 % are traded!
- Production of ammonia responsible for appr. 250 Mt CO₂/a

Belona Report 6, 2002
Hydrogen Today

Space Shuttle Discovery
Start from Pad 39B
Kennedy Space Center, FL
4. July 2006

Vulcain-1
Tests of Rocket Motors
DLR Lampoldshausen

Vulcain-2
Hydrogen Tomorrow

A challenging European hydrogen vision

- Direct H₂ production from renewables; de-carbonised H₂ society
- Increasing de-carbonisation of H₂ production; renewables, fossil fuel with sequestration, new nuclear
- Widespread H₂ pipeline infrastructure
- Interconnection of local H₂ distribution grids; significant H₂
- Public and fuel cell technology market generation

Politics

Research

Industry

Solar Fuels: Hydrogen in the Long-Term Future

Fossil Raw Materials
- Reforming
- Gasification/PrOx
- Cracking

Biomass
- Pyrolyses
- Energetic Utilization

Water
- Open TC-Processes
- Direct Dissociation
- TC-Cycles
- HT-Electrolysis

Transition Processes
- SOLREF (SCR, SOLASYS)
- SOLHycARB

CO2-free Processes
- HYDROSOL 1+2
- HYTHEC + Strom für WH Cycle
- Hi2H2 + Strom

Fuel Cells

Combustion Engines

H₂
Solar Thermal Hydrogen Generation
Criteria for Process Selection

- Feasible Operation Temperature. Between 800 and 1600 K.
- Fast Reactions.
- Availability of Materials.
- High Efficiency.
- Hydrogen Production Cost
- Bench Mark: $H_2$ by Electrolysis with Renewable Power.
CO₂ Reduction Potential by “Solarization” of Established Processes

CO₂ Reduction Potential 30 – 50%

kg/kg

SMR
SSMR
CG
SPCR
H₂-Production by Solar Reforming of Hydrocarbons

\[
\text{Reformer: } \text{CH}_4 + \text{H}_2\text{O} \leftrightarrow \text{CO} + 3\text{H}_2
\]

Flow diagram showing the process of hydrogen production from hydrocarbons using solar reforming. The process involves the following steps:

1. **Hydrocarbons** and **H₂O** enter the reformer.
2. The reformer produces **Syngas (H₂/CO)**.
3. The syngas undergoes a **WGS** reaction to produce **H₂** and **CO₂**.
4. **Gas Separation** to obtain pure **H₂**.
Experimental Results of SOLASYS (EU FP4)
Currently Continued in SOLREF (EU FP6)

- Power to Gas: up to $220 \text{ kW}_{th}$ ($400 \text{ kW}_{th}$)
- Reforming Temperature: up to $765^\circ\text{C}$ ($1000^\circ\text{C}$)
- Operation Pressure: up to 9 bar (15 bar)
- Degree of Methane Conversion: max. 78% acc. to theoretical equilibrium
H₂-Production in TC Cycles

Direct Thermal Dissociation of Water Only Possible at Very High Temperatures:

\[ H₂O \leftrightarrow H₂ + ½O₂ \]

Problems:

- Constant Generation of High Temperatures over Extended Periods
- Materials
- Separation of Products
H₂-Production in TC Cycles

- In TC Cycles Splitting of Water in Several Steps:
  - e.g. Two Steps
    1) \( M_xO_y \leftrightarrow xM + \frac{y}{2}O_2 \)
    2) \( xM + yH_2O \leftrightarrow M_xO_y + yH_2 \)
- Lower Reaction Temperatures than Direct Splitting.
- To Achieve High Efficiencies: not more than three Step Processes.

\[
\begin{align*}
\Delta H & \quad \text{required Energy} \\
T \Delta S & \\
\Delta G & \quad \text{Temperature}
\end{align*}
\]

- H₂O: 4300 K
- TC: 1000-2500K
HYDRSOL + HYDROSOL 2 (EU FP5, FP6)

2 Step Redox Cycle based on Ferritic Materials

1. Endothermal Step (1000-1200°C)
   \[ \text{MO}_{\text{ox}} \leftrightarrow \text{MO}_{\text{red}} + \frac{1}{2} \text{O}_2 \]

2. Water Dissociation (700 - 1000°C)
   \[ \text{MO}_{\text{red}} + \text{H}_2\text{O} \leftrightarrow \text{MO}_{\text{ox}} + \text{H}_2 \]

Redox System:
   \( \text{MO} = (\text{Zn}, \text{Y})\text{Fe}_2\text{O}_4 \) (black)
   \( \text{Y} = \text{Ni} \text{ or } \text{Mn} \)

Cost Estimate:
- Batch-Process 7 €/kg
- Conti-Process 3,5 €/kg
Conti-Reactor Test in DLR‘s Solar Furnace
Quasi-continuous Hydrogen Production in DLR’s Solar Furnace

More than 50 Cycles Realized
Efficiency Potential: HYDROSOL vs. Electrolysis
Summary

- Solar Fuels, in particular Hydrogen, Could Contribute to a Renewable Energy Economy Significantly, Provided that:
  - Proof of Feasibility in Demo-Scale Required for Industrial Acceptance
    - Solar Thermal Processes Promise High Efficiencies
    - Carbon-Based Transition Processes Facilitate Market Approach
  - Hydrogen Storage Essential for Acceptance
  - Accepted Energetic Utilization of Hydrogen in a Large Scale (Fuel Cells, Combustion Engines …)
Thank you for your Attention